IEc

Waste Materials-Flow Benchmark Sector Report: Beneficial Use of Secondary Materials - Coal Combustion Products

Final Report | 15 December 2006

prepared for:

U.S. Environmental Protection Agency

Office of Solid Waste

prepared by:

Industrial Economics, Incorporated

2067 Massachusetts Avenue

Cambridge, MA 02140

617/354-0074

INDUSTRIAL ECONOMICS, INCORPORATED

ACKNOWLEDGMENTS

Industrial Economics, Incorporated (IEc), is responsible for the overall organization and development of this report. This report was developed with the assistance of Dr. Jim Boyd of Resources for the Future, Dave Goss of the American Coal Ash Association (ACAA), and with input and data from various EPA Office of Solid Waste and Office of Policy Economics and Innovation representatives. Lyn. D. Luben of the U.S. Environmental Protection Agency, Office of Solid Waste, provided guidance and review.

TABLE OF CONTENTS

INTRODUCTION AND PROJECT OVERVIEW

The U.S. Environmental Protection Agency's Office of Solid Waste (EPA OSW) is currently considering the strategic direction of solid and hazardous waste policy. As part of this effort, OSW is developing methods to evaluate the environmental, human health, and economic outcomes of specific EPA programs. Three important areas of focus in this transition are:

- Measurement of materials flow and life cycle impacts related to waste minimization and materials recovery and reuse, including an emphasis on "upstream" resource conservation benefits;
- Documentation of the impacts of voluntary programs, including the various efforts and materials targeted by EPA's Resource Conservation Challenge (RCC);[1] and
- Development of data and approaches that can support annual performance reporting under the Government Performance and Results Act (GPRA) and OMB's Performance Assessment Rating Tool (PART) evaluations.

As an initial step in the development of methods to assess program benefits, OSW is examining the extent to which the costs and benefits of recycling and source reduction may be quantified for a range of materials targeted by the RCC. Under RCC, EPA has established three goals for increased beneficial use of coal combustion products (CCPs):

- Achieve a 50 percent beneficial use rate of CCPs by 2011;
- Increase the use of coal fly ash in concrete by 50 percent (from 12.4 million tons per year in 2001 to 18.6 million tons by 2011); and
- Reduce greenhouse gas emissions from concrete production by approximately 5 million metric tons CO_2 equivalent by 2010.[2]

This report provides an initial assessment of the baseline practices, markets, and policies that affect the recovery and use of CCPs. In addition, the report provides an overview of life cycle information available to estimate incremental benefits associated with additional beneficial use. The report is designed as an initial overview of the information available to support an assessment of the specific benefits associated with RCC activities and programs. Ultimately, in combination with specific information about explicit RCC efforts, this report can be used to support the development and implementation of measures of program efficiency.

The report proceeds in four sections. To provide market context for the discussion, the first section characterizes current CCP generation and management, the market structure of beneficial use, and specific EPA efforts to increase beneficial use of CCPs. The second section describes available estimates of the benefits of increased beneficial use using a life cycle approach. The third section considers economic, regulatory, and technical

---

[1] The RCC is an EPA initiative that seeks to identify and encourage innovative, flexible, and protective ways to conserve natural resources and energy. Specifically, the RCC is a cross-Office program that assists in developing voluntary programs that promote the reuse, recycling, and source reduction of materials.

[2] U.S. EPA, "About C2P2," accessed at http://www.epa.gov/epaoswer/osw/conserve/c2p2/about/about.htm.

factors that may account for the current level of beneficial use and discusses how these factors might be addressed. Finally, the report notes potential areas of interest in furthering the examination of benefits related to the beneficial use of CCPs.

BASELINE ASSESSMENT OF WASTE PRACTICES AND TRENDS

The coal-fired power industry is the largest generator of CCPs. Other industries, such as commercial boilers and mineral and grain processors that use coal as a fuel source, also produce small quantities of CCPs. Because these other industries generate such small quantities of CCPs relative to the coal-fired electric power industry, this report focuses solely on the coal-fired electric power industry.

CCPs are categorized by the process in which they are generated, which varies by plant. CCPs include the following materials:

- **Fly ash.** Exhaust gases leaving the combustion chamber entrain fly ash particles during the coal combustion process. To prevent fly ash from entering the atmosphere, power plants use various collection devices to remove it from the gases that are leaving the stack. Fly ash is the finest of coal ash particles.
- **Bottom ash.** With grain sizes ranging from fine sand to fine gravel, bottom ash is coarser than fly ash. Utilities collect bottom ash from floor of coal burning furnaces used in the generation of steam, the production of electric power, or both. The physical characteristics of the product generated depend on the characteristics of the furnace.
- **Flue Gas Desulphurization (FGD) Material.** FGD material results from the flue gas desulphurization scrubbing process that transforms gaseous SO^2, released during coal combustion, to sulfur compounds. Facilities collect these sulfur compounds for beneficial use or safe disposal. Although similar in concept, these processes and materials are characterized as wet or dry, depending on the sorbents used and products generated.
- **Boiler Slag.** Boiler slag consists of molten ash collected at the base of cyclone boilers. Facilities cool boiler slag with water, which then shatters into black, angular pieces that have a smooth appearance.
- **Fluidized Bed Combustion (FBC) Ash.** A fluidized bed combustion boiler, a type of coal boiler that combines the coal combustion and flue gas desulphurization processes within a single furnace, generates FBC ash. FBC ash is rich in lime and sulfur.
- **Cenospheres.** Generated as a component of fly ash in high temperature coal combustion, Cenospheres consist of extremely small, lightweight, inert, hollow spheres comprised largely of silica and alumina that are filled with low-pressure gases.[3] When fly ash is disposed in settlement lagoons, cenospheres can be

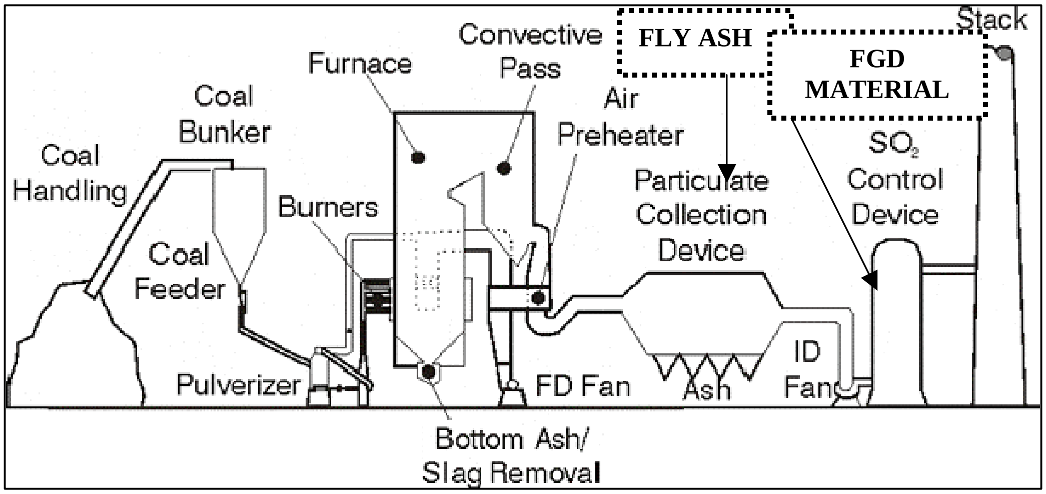
---

[3] Cenospheres range in size from 20 to 5000 microns.

collected on the surface where they can be skimmed for use in manufacturing processes.

At a typical coal-fired power plant, coal combustion generates CCPs during several phases of the process. Exhibit 1 illustrates the collection for several types of CCPs. As shown below, facilities remove bottom ash and boiler slag from the base of the furnace. Fly ash accumulates in the particulate collection device, while FGD material collects in the SO_2 control device.

EXHIBIT 1 COAL COMBUSTION PROCESS AT A COAL-FIRED POWER PLANT



Source: Energy Information Administration, accessed at: www.eia.doe.gov.

CURRENT QUANTITIES GENERATED AND MANAGED

In 2005, the coal-fueled electric power industry generated approximately 123 million tons of CCPs. Of these, the industry disposed of approximate 74 million tons to landfills, while beneficially using approximately 50 million tons in products. Exhibit 2, below, presents the current quantities of CCPs in context of other materials targeted by the RCC. Except for construction and demolition debris, the U.S. generates larger quantities of CCPs than other industrial and municipal sold waste (MSW).

EXHIBIT 2 RCC MATERIALS BY QUANTITIY

MATERIAL[a]	QUANTITY GENERATED (MILLION TONS)	QUANTITY RECOVERED/ BENEFICIALLY USED[b] (MILLION TONS)	QUANTITY DISPOSED (MILLION TONS)	YEAR
C&D Debris[1]	331	196	136	2003
CCPs[2]	**123**	**50**	**74**	**2005**
Paper and Paperboard[3]	83	40	43	2003
Packaging[3]	74	29	45	2003
Organics[3]	56	17	39	2003
Foundry Sand[4]	6 to 10	0.5	5.5 to 9.5	2002
Chemicals[5]	0.04	NA	NA	2003

Notes:

a. Under the RCC 2005 Action Plan, beneficial use of secondary materials, and reduction of priority and toxic chemicals are also included. As such, we have included these material streams in this exhibit, even though C&D debris, CCPs, foundry sand, and chemicals are not considered MSW.

b. The figures shown for paper and paperboard, packaging, and organics are the quantities recovered from the municipal solid waste (MSW) stream. The figures shown for C&D debris, CCPs, and foundry sand are quantities that are beneficially used.

Sources:

1. US EPA, "Characterization of Building-Related Construction and Demolition Debris in the United States" and "Characterization of Road-related Construction and Demolition Debris in the United States," 2005. (Note that these documents are preliminary and are currently undergoing peer-review).
2. American Coal Ash Association, "2004 Coal Combustion Product (CCP) Production and Use Survey," accessed on October 29, 2006 at: <http://www.acaa-usa.org/PDF/2004_CCP_Survey(9-9-05).pdf>.
3. US EPA, "Municipal Solid Waste in the United States: 2003 Data Tables," Table 1, accessed on October 26, 2006 at: <http://www.epa.gov/epaoswer/non-hw/muncpl/pubs/03data.pdf>.
4. Foundry Industry Recycling Starts Today, "What is Recycled Foundry Sand?", accessed on September 20, 2006 at: <http://www.foundryrecycling.org/org/whatis.html>.
5. US EPA, "Draft National Priority Trends Report (1999-2003) Fall 2005," as reported in the NPEP GPRA 2008 database of TRI data from 1998-2003.

The American Coal Ash Association (ACAA), a trade association whose purpose is to advance the beneficial use of CCPs, conducts an annual survey of coal-fired electric plants to collect data on the production, disposal, and use of CCPs.[4] Exhibit 3 summarizes the 2005 survey on generation, disposal, and beneficial use of various CCP categories.

[4] The ACAA survey is administered to ACAA members only, which account for approximately 40 percent of private power generation. Not all ACAA members complete the survey each year. ACAA extrapolates survey respondent data to the entire coal-fired electricity generation industry.

EXHIBIT 3 SUMMARY OF CCP GENERATION AND MANAGEMENT (2005)

PRODUCT	CCPS GENERATED (TONS)	BENEFICIALLY USED (TONS)	PERCENT USED	QUANTITY DISPOSED (TONS)[a]	PERCENT DISPOSED
Fly Ash	71,100,000	29,118,454	41%	41,981,546	59%
Flue Gas Desulfurization (FGD) Material	31,102,263	10,116,747	33%	20,985,516	67%
FGD Material--Wet Scrubbers	*17,700,000*	*689,184*	*4%*	*17,010,816*	*96%*
FGD Gypsum	*11,975,000*	*9,268,365*	*77%*	*2,706,635*	*23%*
FGD Material--Dry Scrubbers	*1,427,263*	*159,198*	*11%*	*1,268,065*	*89%*
Bottom Ash	17,600,000	7,541,972	43%	10,058,028	57%
Boiler Slag	1,957,392	1,890,809	97%	66,583	3%
Fluidized Bed Combustion (FBC) Ash	1,366,438	944,559	69%	421,879	31%
Cenospheres[b]	Not available	78,175	Not available	Not available	Not available
Total CCPs	**123,126,093**	**49,612,541**	**40%**	**73,513,552**	**60%**

Notes:
a. Calculated by subtracting quantity beneficially used from quantity generated.
b. The ACAA's "CCP Production and Use Survey" does not report total generation or disposal quantities for cenospheres.
Source:
1. American Coal Ash Association. "2005 Coal Combustion Product (CCP) Production and Use Survey," accessed at: http://www.acaa-usa.org/PDF/2005_CCP_Production_and_Use_Figures_Released_by_ACAA.pdf.

Exhibit 3 illustrates several important aspects of the generation, beneficial use, and disposal of CPPs:

- Fly ash constitutes the largest proportion (58 percent) of CCP materials generated in 2005. FGD material follows at 26 percent. Bottom ash, boiler slag and FBC ash collectively comprise the remaining 17 percent of CCPs generated in 2005.
- Boiler slag and FGD gypsum have the highest percentage of beneficial use of any coal combustion product.
- Fly ash, FGD material (other than FGD gypsum), and bottom ash have the highest disposal rates.

Beneficial Use Options

The chemical and physical properties of CCPs allow for their use in a wide range of products. CCPs may be used as a component of building materials or as a replacement for other virgin materials such as sand, gravel, or gypsum. The physical properties of CCPs make them especially useful for construction and industrial materials. Size, shape, and chemical composition determine the suitability of these materials for beneficial use. Higher value applications, such as use in cement or concrete products, require moderately stringent specifications (in terms of size, shape and chemical composition), whereas lower value uses, such as structural or mining fills, can accept more variable materials. For this reason, EPA has found that lower technology applications that require large volumes of CCPs may present the greatest potential for beneficial use.[5]

Exhibit 4, below, illustrates the distribution of various types of CCPs across major beneficial use categories. The applications highlighted in the exhibit represent approximately 80 percent of the current use of CCPs.[6] We include an expanded version of this table, which details a more inclusive set of CCP beneficial use applications in Appendix A.

[5] EPA. 1999. "Report to Congress: Wastes from the Combustion of Fossil Fuels." Vol. II. EPA-530-R-99-010, March 1999.

[6] Relatively minor applications comprise the remaining 20 percent of CCP beneficial uses. These applications include use such as soil stabilizers, mineral filler in asphalt, and mine reclamation.

EXHIBIT 4 KEY BENEFICIAL USE APPLICATIONS FOR CCPS IN 2005 (TONS)

USE APPLICATION (INDUSTRY)	FLY ASH	BOTTOM ASH	FGD GYPSUM	FGD - WET	FGD - DRY	BOILER SLAG	FBC ASH	TOTAL	SUBSTITUTES
Concrete[a] (Construction)	14,989,958	1,020,659	328,752	0	13,965	0	0	16,353,334	Cement
Wallboard[b] (Construction)	0	0	8,178,079	0	0	0	0	8,178,079	Natural gypsum
Structural fill[c] (Construction)	5,710,749	2,321,140	0	0	2,666	175,144	140,300	8,349,999	Sand, Gravel, Soil
Cement mix additive[d] (Construction)	2,834,476	939,667	397,743	782	0	42,566	0	4,215,234	Clay, Soil, Shale, Gypsum
Waste stabilization[e] (Waste Mgmt)	2,657,046	42,353	0	0	0	0	140,555	2,839,954	Cement Lime, Cement kiln dust
Blasting Grit/Roofing Granules	0	89,109	0	0	0	1,544,298	0	1,633,407	Sand
Use Totals	*26,192,229*	*4,412,928*	*8,904,574*	*782*	*16,631*	*1,762,008*	*280,855*	*41,570,007*	--
Other use totals[f]	*2,926,225*	*3,129,044*	*363,791*	*688,402*	*142,567*	*128,801*	*663,704*	*8,042,534*	--
Combined Use Total	*29,118,454*	*7,541,972*	*9,268,365*	*689,184*	*159,198*	*1,890,809*	*944,559*	*49,612,541*	--
Quantity Generated	*71,100,000*	*17,600,000*	*11,975,000*	*17,700,000*	*1,427,263*	*1,957,392*	*1,366,438*	*123,126,093[g]*	--
CCP Utilization Rate[h]	*41%*	*43%*	*77%*	*4%*	*11%*	*97%*	*69%*	*40%*	--

Notes:

a. CCPs are frequently used as a replacement for a portion of Portland cement in the manufacture of concrete, giving it improved strength and durability.

b. FGD is used as a substitute for virgin gypsum in wallboard manufacturing.

c. Structural fill is an engineered material that is used to raise or change the surface contour of an area and to provide ground support beneath highway roadbeds, pavements and building foundations. It can also be used to form embankments.

d. As an additive in Portland cement, CCPs retard setting, which enables wet cement in ready-mix trucks to be transported greater distances while remaining workable.

e. The chemical properties of CCPs make them effective stabilizers of biosolids (sludge from municipal waste water treatment).

f. Includes quantities beneficially used in minor applications not included in this exhibit, but listed in Appendix A.

g. Includes 115,596 tons of "Other FGD Material" not listed in this table because of the small quantities generated.

h. CCP utilization rates reflect all use applications, some of which are omitted from this table but are included in Appendix A. Utilization rates are calculated by dividing the total quantity used by the total quantity generated.

Sources:

1. American Coal Ash Association. "2005 Coal Combustion Product (CCP) Production and Use Survey," accessed at: http://www.acaa-usa.org/PDF/20045_CCP_Production_and_Use_Figures_Released_by_ACAA.pdf.

2. Western Region Ash Group, "Applications and Competing Materials, Coal Combustion Byproducts," accessed at: http://www.wrashg.org/compmat.htm.

Exhibit 3 illustrates several important aspects regarding the beneficial use options for CCPs:

- Concrete, wallboard, structural fill, cement, and waste stabilization comprise the highest volume beneficial uses of CCPs.
- The use of fly ash as a pozzolanic binder in concrete represents the largest beneficial use application.[7] Fly ash can be a valuable additive to concrete mixtures that enhances the strength, durability, and workability of the concrete product.[8]
- FGD material serves as a substitute for virgin gypsum in wallboard construction. This high value use represents the second largest use of CCPs, by volume, and second highest utilization rate at 77 percent.
- Although one of the smaller material streams, facilities beneficially use boiler slag at the highest rate. Boiler slag possesses two key properties that make it ideal for beneficial use: (1) the highly uniform quality of boiler slag increases its acceptance among potential end-users; and (2) boiler slag's unique abrasive properties make and excellent material for blasting grit and asphalt shingles.[9]

In comparison to the same ACAA survey conducted in 2004, the total overall CCP utilization from 2004 to 2005 has increased slightly (0.21 percent). However, it is important to note that both the generation and beneficial use of CCPs increased during this time period. Both bottom ash and wet FDG material saw modest decreases in beneficial use rates (4 percent and 3 percent, respectively). Boiler slag utilization gained the highest over the time period, with an increase in beneficial use of seven percent.[10,11]

MARKET STRUCTURE OF MATERIAL GENERATION AND MANAGEMENT

Many of the factors that effect beneficial use of CCPs are related to the underlying structure of markets affecting its generation and management. Three main groups participate in the CCP market: (1) coal-fired utilities, (2) independent CCP marketers and consultants, and (3) end-users. In addition, state regulators determine the extent to which CCPs can be beneficially used by defining the regulatory context in which these actors

---

[7] Fly ash is technically a pozzolanic, not a cementitious material. A cementitious material, such as Portland cement, is one that hardens when mixed with water. A pozzolanic material will also harden with water but only after activation with an alkaline substance such as lime. The combination of Portland cement and water in concrete mixtures creates two products: a durable binder that "glues" concrete aggregates together and free lime. Fly ash reacts with this free lime to create more of the desirable binder.

[8] Personal communication with Tom Pyle, Caltrans, , November 2006.

[9] EPA. "Boiler Slag," accessed at: http://www.epa.gov/epaoswer/osw/conserve/c2p2/about/about.htm.

[10] American Coal Ash Association. "2005 Coal Combustion Product (CCP) Production and Use Survey," accessed at: http://www.acaa-usa.org/PDF/20045_CCP_Production_and_Use_Figures_Released_by_ACAA.pdf. and "2004 Coal Combustion Product (CCP) Production and Use Survey," accessed at: http://www.acaa-usa.org/PDF/2004_CCP_Survey(9-9-05).pdf.

[11] More efficient furnace types that use pulverized coal are replacing the cyclone and slag-tap furnaces that typically produce boiler slag. The replacement of these boiler types is decreasing the available supply of boiler slag. EPA. "Boiler Slag," accessed at: http://www.epa.gov/epaoswer/osw/conserve/c2p2/about/about.htm.

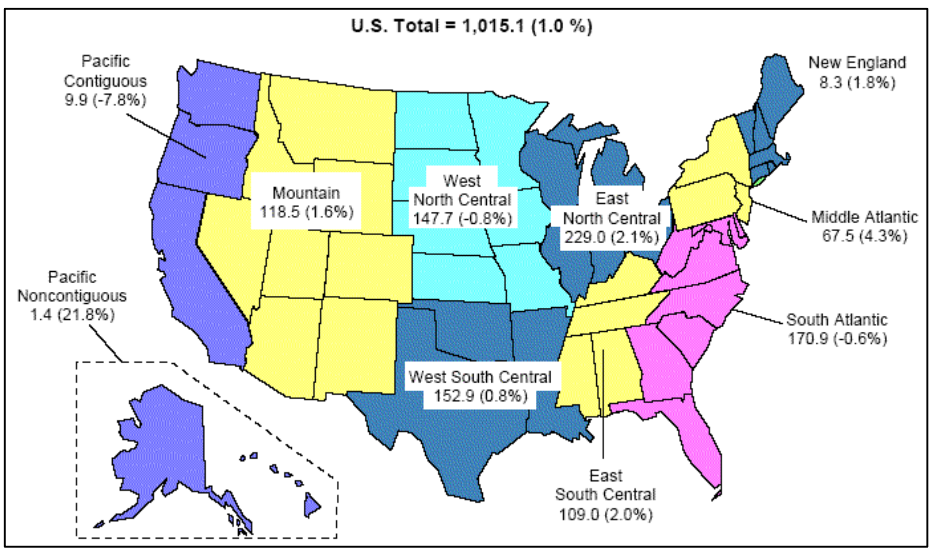
operate. This section considers the factors affecting beneficial use decisions among these groups and illustrates these considerations for the top three beneficial use applications.

Coal-Fired Utility Practices: CCP Supply

The coal-fired power industry is the largest generator of CCPs in the U.S. As noted previously, other industries that use coal as a fuel source in commercial or industrial boilers (e.g., mineral and grain processors) also produce small quantities of CCPs. Coal-generated electricity supplies approximately 50 percent of the electricity consumed in the U.S.[12] Since electricity demand is projected to increase by 40 percent by 2020 and coal will continue to be an important fuel source, it is likely that the quantity of CCPs produced and available for beneficial reuse will also increase.[13,14]

Approximately 400 to 500 coal-fired electric utilities currently operate in the U.S.[15] Exhibit 5 shows the geographic distribution of coal consumption by electric power plants across the U.S.

EXHIBIT 5 ELECTRIC POWER SECTOR CONSUMPTION OF COAL IN 2004, BY CENSUS REGION (MILLION SHORT TONS AND PERCENT CHANGE FROM 2003)



Source: Energy Information Administration, accessed at: www.eia.doe.gov.

As shown in Exhibit 5, coal consumption by power plants is greatest in the East North Central region of the U.S., but consumption remains relatively high throughout the entire Central and Southern United States. Coal consumption is low in the Contiguous and Noncontiguous Pacific regions of the U.S. and in New England.

---

[12] American Coal Foundation, "All About Coal: Fast Facts About Coal," accessed at: http://www.teachcoal.org/aboutcoal/articles/fastfacts.html.

[13] Center for Energy and Economic Development, "Growing Demand," accessed at: http://www.ceednet.org/ceed/index.cfm?cid=7500,7582.

[14] American Coal Foundation, "Coal's Past Present and Future," accessed at: http://www/teachcoal.org/aboutcoal/asrticles/coalppf.html.

[15] Personal communication with Dave Goss, American Coal Ash Association, April 2006.

CCP generation closely approximates the geographic distribution of coal consumption across the U.S., but CCP generation is not directly proportional to coal consumption. The composition of coal varies regionally in the U.S. For example, the non-combustible portion (commonly referred to as "ash") of Western bituminous coal is higher than that of Western sub-bituminous coal (approximately 10-15 percent and 4-6 percent ash, respectively). Coal with a higher non-combustible ash content will yield greater quantities of CCPs when combusted.

Several factors influence a utility's decision to supply CCPs for beneficial use. Economic factors are the primary consideration and include:

- **Landfill disposal costs.** For many utilities, the sale of CCPs for beneficial use is a means of reducing operating costs through avoidance of landfill tipping fees. In order for beneficial use of CCPs to be competitive, the cost of reselling CCPs, minus revenue from the sale, must be less than the cost of landfill disposal. Landfill tipping fees vary regionally but range from $5 per ton to $45 per ton.[16] Avoiding landfill disposal costs may be a significant incentive for a utility to engage in beneficial use.
- **Revenue from sale.** Depending on the type of CCP, an electric utility may or may not receive revenue for its ash. For some CCP types, marketers will accept ash as a service to the plant (allowing the plant to avoid disposal costs) but do not pay for the ash. For other CCP types, especially fly ash, boiler slag and cenospheres, the revenue received can be a significant incentive for a utility to market its ash.[17]
- **Transport costs.** CCPs are heavy materials, which makes transport over long distances expensive. Transport distance between the utility and the nearest landfill or end-user is a significant determinant in the management of CCPs.
- **Processing costs.** Approximately 90 percent of CCPs do not require processing prior to beneficial use. Higher value applications, such as the use of fly ash in concrete, require processing to meet material specifications.
- **Storage costs.** In many parts of the country, the production of coal ash is high during both the coldest and hottest months of the year when people are heating and cooling their homes, offices and schools. However, the winter season is often the slowest period for construction and other applications that beneficially use the ash. As a result, it is necessary to store CCPs until it can be utilized. Typically, domes are inflated adjacent to boilers for the CCP collection. The cost of storing fly ash or other CCPs during the winter months may be a deterrent to beneficial use by a utility.
- **Marketing costs.** In order to attract buyers of CCPs, a utility must devote financial resources to marketing their CCP product(s) for beneficial use. Some

[16] Personal communication with Dave Goss, American Coal Ash Association, April 2006.

[17] Personal communication with Dave Goss, American Coal Ash Association, May 2006.

utilities market their CCPs directly to end-users, but others pay a third party marketer or broker to negotiate CCP sales.

Intermediaries

As stated above, many coal-fired electric generators market their CCPs through a third-party marketer instead of selling directly to the end-user. In these cases, a utility perceives an efficiency in outsourcing the marketing of its CCPs. Marketers typically accept all of a generator's CCPs as a service to the company, sell the marketable portion, and dispose of the portion that is not salable. The marketer typically bears the cost of hauling CCPs from the utility.

End-Users and Purchasers: CCP Demand

Several factors influence an end-user's decision to use CCPs in their product. Such considerations include:

- **Price of CCPs relative to the price of virgin materials.**[18] If the price of a virgin material is less than the price of CCPs (which will reflect cost factors such as transport distance, processing and storage costs), end-users will purchase virgin materials. In areas where virgin materials are abundant and inexpensive, CCPs may not be economically viable. Exhibit 6 shows the typical price ranges for CCPs used in various applications relative to the virgin material it replaces.

[18] Note that the "price" of CCPs represents how much an end-user would pay for the product.

EXHIBIT 6 SAMPLE CCP AND VIRGIN MATERIAL PRICES FOR CCP APPLICATIONS

VIRGIN MATERIAL	2005 AVG PRICE, (PER TON, FREE ON BOARD)[a,b]	CCP SUBSTITUTE	2005 AVG PRICE, (PER TON, FREE ON BOARD)[a]
Portland cement	$80	Concrete quality fly ash	$0 to $45 per ton
		Boiler slag	Not available
Virgin aggregate for fill	$3	Fly ash for flowable fill	$1 per ton
Virgin aggregate for road base	$5	Bottom ash or fly ash for road base	$4 to $8 per ton
Lime for soil stabilization (Hydrated lime)	$83	Fly ash for soil stabilization	$10 to $20 per ton
Lime for waste stabilization (Quicklime)	$66	Fly ash for waste stabilization	$15 to $25 per ton
Virgin aggregate for snow and ice control	$5	Bottom ash for snow and ice control	$3 to $6 per ton
Gyspsum for wallboard interior	$21	FGD Gypsum	Not available

Notes:
a. Virgin material prices are reported by USGS while CCP prices are provided by ACAA. This price data represents the best available information, should be cross-compared with caution, as the data may not capture all factors driving price variability.
b. "Free on Board" is a shipping term, which indicates that the supplier pays the shipping costs (and usually the insurance costs) from the point of manufacture to a specified destination, at which point the buyer takes responsibility.

Sources:
1. USGS, "Mineral Commodities Summary 2006: Cement," accessed at: http://minerals.usgs.gov/minerals/pubs/commodity/cement/cemenmcs06.pdf
2. USGS, "Mineral Commodities Summary 2004: Construction Sand and Gravel," accessed at: http://minerals.usgs.gov/minerals/pubs/commodity/sand_&_gravel_construction/sandgmyb04.pdf
3. USGS, "Mineral Commodities Summary 2005: Lime," accessed at: http://minerals.usgs.gov/minerals/pubs/commodity/lime/lime_myb05.pdf
4. USGS, "Mineral Commodities Summary 2006: Gypsum," accessed at: http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/gypsumcs06.pdf
5. American Coal Ash Association, "Frequently Asked Questions," accessed at: www.acaa-usa.org

- **Technical fit between CCPs and use application.** CCPs have varying physical and chemical characteristics due to differences in the types of coal, coal combustion processes, air pollution control technologies, and CCP management practices at individual power plants. For example, high carbon content or the presence of air emission additives may render CCPs unsuitable for some use applications.
- **Sufficient quantities of CCPs.** Some beneficial use applications require larger volumes of CCPs than are typically produced at a single power plant. Where demand for CCPs is greater than the supply generated by a single plant, the end-user may need to purchase CCPs from multiple suppliers; this can increase transaction costs.

- **State Regulations.** Regulations governing beneficial use of CCPs vary by state. In many states, beneficial use of CCPs must be approved on a project-by-project basis. Currently, public and environmental health considerations drive state regulatory decisions concerning beneficial use of CCPs in end-use applications.[19,20]

- **Incomplete science.** In absence of definitive data on health risks associated with the beneficial use of CCPs, some states have chosen to limit the use of CCPs in building materials. For example, EPA research has found that CCPs may release small quantities of mercury to the ambient air.[21] Noting this research, States have questioned the safety of using fly ash in cement to be used in schools.[22]

Market Dynamics of Specific Use Applications

The supply and demand characteristics of CCPs make them better suited to some beneficial uses than others. The economic viability of the top three beneficial uses (by volume) is considered individually below. Concrete, gypsum wallboard, and structural fill are all long-standing, widely accepted uses for CCPs.

Concrete

Fly ash can be a valuable additive to concrete mixtures to enhance the strength, durability, and workability of the product.[23] Fly ash substitutes directly for Portland cement in the concrete mixing process. This beneficial use represents the highest value application for CCPs and has potential to increase as result of the current high demand for cement in the U.S.[24,25]

Processing costs are a significant consideration for the beneficial use of fly ash in concrete. In order for fly ash to be marketable for use in concrete, it must be processed to remove excess carbon. Due to the Clean Air Act and Amendments (CAAA), utilities have installed systems to reduce air emissions. The use of low NO_x burners and other

---

[19] Energy & Environmental Research Center, University of North Dakota, "Review of Florida Regulations, Standards, and Practices Related to the Use of Coal Combustion Products: Final Report," April 2006, accessed at: http://www.undeerc.org/carrc/Assets/TB-FLStateReviewFinal.pdf.

[20] Some states, such as Wisconsin, have set up regulatory schemes designed to speed up the approval process for products using beneficial use materials such as CCPs. Currently, Wisconsin requires initial leachate testing of the material to be beneficially used, which leads to a specific rating. Materials that fall into a standard rating class are automatically approved for specific uses. For example, material found to meet drinking water standards can be used in any application, whereas material found to have a moderate level of contamination, may only be approved for encapsulated uses. Users are also required to submit annual reports. Personal communication with Bizhan Sheikholeslami, Wisconsin Department of Natural Resources, November 2006.

[21] Hassett, David J., Debra F. Pflughoeft-Hassett, Dennis L. Laudal, and John H. Pavlish. 1999. Mercury Release from Coal Combustion ByProducts to the Environment.

[22] Personal Communication with Lyn Luben, EPA, July 2006.

[23] Personal communication with Tom Pyle, Caltrans, , November 2006.

[24] The cement shortage in the U.S. is a result of both increased domestic construction activity and strong demand by growing foreign economies (especially China).

[25] Portland Cement Association. "FAQ: Cement Supply Shortage," accessed at: http://www.cement.org/pca/shortageQA.asp. We contacted two industry experts, Dave Goss of the American Coal Ash Association and Barry Deschenaux of Holcim Cement, to elaborate on this trend (increased use of coal ash in cement due to domestic and foreign demand), but neither was able to provide more detailed information on the extent to which this might occur in the future.

NO_x reduction technologies typically increases the amount of unburned carbon remaining in fly ash. The introduction of more carbon, in turn, increases the processing costs required to make the fly ash suitable for use in concrete.[26] In addition, two recently promulgated clean air rules may potentially affect the supply and/or cost of fly ash for use in concrete:

- **Clean Air Mercury Rule (CAMR).** Under CAMR, coal fired power plants must control mercury emissions. Recent research suggests that most facilities will rely on activated carbon injection technology to accomplish this task, which may increase concentrations of mercury, arsenic, and selenium in fly ash. Laboratory testing suggests that these increased concentrations are unlikely to pose a significant threat to human health or the environment relative to baseline conditions. However, the activated carbon systems are likely to render fly ash produced by such systems unmarketable because they reduce the air entrainment potential of the fly ash, which in turn reduces its structural rigidity when cured. Utilities could avoid this problem by installing additional equipment to remove fly ash from coal combustion gases prior to carbon injection. Assuming that utilities would be averse to the additional processing costs, fly ash produced in response to CAMR may be unfit for beneficial use. However, according to the regulatory impact analysis developed in support of the rule, utilities are expected to retrofit no more than 12 percent of their coal-fired generating capacity with activated carbon by the year 2020. Therefore, the rule may potentially affect no more than a fraction of the fly ash produced by utilities.[27]
- **Clean Air Interstate Rule (CAIR).** Under CAIR, coal-fired power plants must install systems to further control SO_2 and NO_X emissions. To control SO_2 emissions, coal-fired power plants may install scrubbers (FGD systems) or switch from high-sulfur to low-sulfur coal. To control NO_X emissions, utilities will likely install systems that employ an ammonia reaction to turn NO_X into nitrogen gas and water. Recent research suggests that the quantity and quality of fly ash produced under these conditions will not be significantly affected and the marketability of fly ash will remain the same under CAIR.[28]

In addition, for fly ash use in concrete, storage costs are another important consideration. As noted earlier, concrete production generally mirrors construction activity, which is seasonal in many parts of the country. Because CCPs are generated continuously, the utilities' capacity to store the material during the construction off-season can be a significant consideration. Costs of storing large volumes of CCPs increase the costs of beneficial use.

---

[26] Carbon content is one of the parameters used to determine concrete performance, high-carbon ash often will not meet American Society for Testing and Materials (ASTM) standards for concrete use. Glenn, John, David Goss and John Sager. "C2P2--Partnership Innovation."

[27] Jason Price and Mark Ewen, Industrial Economics, Inc. Memorandum to Lyn Luben, EPA, "Impact of CAIR and CAMR on the Quantity and Quality of Coal Combustion Fly Ash Generated by Affected Facilities." December 1, 2006.

[28] Jason Price and Mark Ewen, Industrial Economics, Inc. Memorandum to Lyn Luben, EPA, "Impact of CAIR and CAMR on the Quantity and Quality of Coal Combustion Fly Ash Generated by Affected Facilities." December 1, 2006.

Gypsum Wallboard

Utilization of FGD material (often called synthetic gypsum) in wallboard manufacture is a well-established market. Because the quality of FGD material produced by power plants is generally consistent, wallboard manufacturers often locate their facilities adjacent to power plants to allow FGD material to be delivered directly to the wallboard plants. In many cases, wet FGD material is piped directly to the adjacent wallboard facility, which significantly reduces transport and handling costs. Given these developments, the supply of synthetic gypsum will likely remain high, and may possibly increase as new wallboard manufacturing facilities are being constructed to accommodate synthetic gypsum (derived from FGD material) in wallboard production.[29]

Structural Fill

Structural fill is an engineered material used to raise or change the surface contour of an area and to provide ground support beneath highway roadbeds, pavements, embankments and building foundations. Structural fill is a low-value use of CCPs, and as such, the quality standards are lower than that of high-value applications such as concrete. Consequently, CCPs destined for use in structural fill generally do not require processing, which keeps costs low.

Demand for CCPs in structural fill applications is variable and generally occurs on a project-by-project basis. One large construction project using CCPs in fill can create a spike in demand for CCPs, but this may be followed by a lull in demand until another sizeable project can be identified.[30] Because CCPs are generated continuously, the generator's or marketer's capacity to store and accumulate the material between projects is a significant determinant in the use of CCPs in structural fill.

Assessment of Homeland Security Issues

The beneficial use market for CCPs may be affected in the event of a natural disaster or act of terrorism. A disaster may present opportunities for the use of CCPs as part of the reconstruction process. These opportunities would likely depend on the market dynamics that drive the broader use of these materials as previously discussed in this report. Conversely, a natural disaster or terrorist attack on structures that produce, store, or are constructed from CCPs, may release these materials into the environment. The impact of this potential release on human health and environment will likely depend on the types of material released and specific exposure scenarios.

CURRENT EPA PROGRAMS ADDRESSING CCP BENEFICIAL USE

Under the RCC, EPA established goals for beneficial use of CCPs (as enumerated in the introduction) and established the Coal Combustion Products Partnership (C2P2) to help reach these goals. C2P2 is a cooperative effort among EPA, the American Coal Ash Association, the Utility Solid Waste Activities Group (USWAG), the U.S. Department of Energy (DOE), and the U.S. Federal Highway Administration (FHWA). Through C2P2, EPA and its co-sponsors work with all levels of government, as well as industry

[29] Electric Power Research Institute, "Environmental Focus: Flue Gas Desulfurization By-Products," 1999.

[30] Personal communication with David Goss, American Coal Ash Association, March 2006.

organizations, to identify and address regulatory, institutional, economic, informational, and other limiting factors to the beneficial use of CCPs. Specifically, the program includes the following initiatives and activities:

- **The C2P2 Challenge:** Under the C2P2 challenge, partners are eligible for awards recognizing activities such as documented increases in CCP use and successes in CCP promotion and utilization.
- **Barrier Breaking Activities:** C2P2 addresses limiting factors to increased CCP utilization through activities such as developing booklets and web resources on the benefits and impacts of using CCPs in highway and building construction applications; publishing case studies on successful beneficial use of CCPs; supporting Green Highways; and updating a manual for highway engineers on the use of fly ash in highway applications.
- **Technical Assistance:** C2P2 has conducted a series of workshops with FHWA, EPA, DOE, ACAA and other partners to provide technical assistance and outreach to support the use of CCPs in concrete highway construction. These workshops present the technical feasibility of using CCPs and the economic and environmental benefits that result from their use.

ANALYSIS OF BENEFITS

To evaluate the achievements associated with EPA efforts to promote beneficial use of CCPs, it is important to assess the environmental and human health impacts of increased recycling and reuse. Life cycle analysis/assessment (LCA) is one tool that can be used to support the evaluation of program benefits. This section provides a brief overview of the role of LCA in the broader economic analysis of benefits, and includes an initial life cycle-based assessment of the potential benefits associated with the beneficial use of fly ash as an input to concrete.

THE RELATIONSHIP BETWEEN LIFE CYCLE AND ECONOMIC BENEFIT ASSESSMENT

Life cycle assessment can be an effective performance assessment tool; LCA describes physical outcomes that can be used to assess environmental impacts and measure progress over time. Because LCA is a systems approach to assessment, it represents an improvement over less comprehensive techniques. However, in economic terms, LCA is only one (albeit central) component of a true analysis of economic benefits.

The RCC and other EPA programs are designed to facilitate changes in the economics of waste generation, handling, and disposal (e.g., by promoting market opportunities for beneficial use). Changes in economic drivers (e.g., raw material prices, other input costs (including transport), competitive factors, regulation, technology, etc.) can lead to changes in the physical system of production. LCA depicts production as a system of complex physical outcomes, and can predict the incremental physical consequences of a change in waste management practices, technology, or price incentives. In LCA, as in reality, one change in the physical system (such as the substitution of fly ash for virgin cement) leads to a corresponding cascade of impacts and shifts – as inputs are substituted, exposure pathways are changed, and technology adapts. LCA can describe the net result of these changes, capturing the incremental effect on physical outputs such as air emissions and energy and water use.

LCA is a natural starting point in the assessment of program benefits, particularly in the context of performance measurement. It reflects a systems approach, allows measurement of changes to baseline conditions, identifies tradeoffs, and yields concrete, measurable metrics that can be evaluated both in isolation and comparatively, across programs and activities. However, while it can provide a clear assessment of beneficial (and other) program impacts, LCA does not itself measure the social benefits and costs of changes in practice. A complete assessment of benefits requires the application of economic valuation techniques to the physical outputs of LCA analysis.

Economic assessment is ultimately important because an accounting of physical outcomes does not describe what those outcomes imply for human well-being. For example, an LCA can describe changes in the quantity of water used in a process, but does not identify the effect of water consumption on well-being. This depends upon the specific location, timing, and quality of the water that is consumed. The value of that water depends on how it would otherwise be used – for human consumption, industrial uses, habitat support, irrigation, and so forth. [31]

Unfortunately, the translation of physical changes into economic outcomes is costly, difficult, and often controversial when applied to human health or environmental outcomes. It frequently requires location-specific data on releases and exposures, as well as well-documented links between these exposures and health or environmental impacts. As noted above, we do not calculate these benefits in dollar terms because monetizing involves complex valuation procedures. Assigning an economic value to even a small set of physical impacts can be a significant and expensive undertaking.[32]

Accordingly, LCA can represent not only a necessary ingredient, but also a practical initial alternative to a complete economic benefit assessment. While economic benefits are the ultimate performance measure, businesses and governments routinely rely on simpler – though imperfect – proxies to facilitate management and performance assessment. As proxies, LCA outputs can represent a legitimate and defensible measure of program impacts. Below we provide an initial assessment of the environmental impacts associated with achieving RCC goals, using available LCA tools. A more detailed discussion of the role of LCA in economic benefits assessment is provided in Appendix B.

---

[31] Hendrickson, Lave, and Matthews (2006) notes the limitation of LCA outputs that are not linked to specific locations and exposures - "A typical [Life Cycle Inventory] of air pollution results in estimates of conventional, hazardous, toxic, and greenhouse gas emissions to the air. Even focused on this small subset of environmental effects, it is unclear how to make sense of the multiple outputs and further how to make a judgment as to tradeoffs or substitutions of pollutants among alternative designs." p. 29.

[32] In the ecological realm, these kinds of translations are underdeveloped. The agency is aware of this ongoing limitation. For example, this conclusion has been drawn from several recent SAB reports, including EPA-SAB. 2003. "Underground Storage Tanks (UST) Cleanup & Resource Conservation & Recovery Act (RCRA) Subtitle C Program Benefits, Costs, & Impacts (BCI) Assessments: An SAB Advisory." (EPA-SAB-EC-ADV-03-001) and "Advisory on EPA's Superfund Benefits Analysis." (EPA-SAB-ADV-06-002). In addition, the SAB Committee on Valuing the Protection of Ecological Systems and Services is currently examining methods for addressing these limitations.

INITIAL ASSESSMENT OF BENEFICIAL USE OF FLY ASH IN CONCRETE

Fly ash contributes the largest quantity of CPP waste. Thus, analysis of the environmental and human health impacts of the beneficial use of this material in concrete applications is a useful starting point for evaluating the potential benefits of beneficial use.[33]

We conducted a comprehensive review of available data sources and tools for assessing life cycle benefits of the use of fly ash in concrete. We identified the Building for Environmental and Economic Sustainability (BEES) model as the most comprehensive and well documented modeling tool currently available for this purpose.[34] BEES was developed by the National Institute of Standards and Technology (NIST) with support from EPA to allow designers, builders, and product manufacturers to compare the life cycle environmental, and economic performance of alternative building products.[35] BEES includes environmental performance data for two types of concrete applications: structural building products (e.g., concrete columns, beams, walls, and slab on grade) and parking lot pavement. The user can compare the environmental performance data of each of these products using different pre-determined concrete mix-designs, some of which include fly ash.

The BEES environmental performance data are quantified estimates of the energy and resource flows going into the product and the releases to the environment coming from the product, summed across all stages of the product life cycle for one cubic yard of concrete. BEES quantifies these flows for hundreds of environmental metrics, but to capture the general spectrum of impacts, we focus on the following:

- Total primary energy use (mj)
- Renewable energy use (mj)
- Nonrenewable energy use (mj)
- Water use (l)
- CO_2 emissions (g)
- Methane emissions (g)
- CO emissions (g)
- NO_X emissions (g)
- Sox emissions (g)
- Particulate emissions (g)
- Hg emissions (g)
- Pb emissions (g)

---

[33] Ideally, this initial assessment would also include a benefits analysis of the beneficial use of FGD material, since a high percentage of this material is beneficially used. Currently, limitations in data availability and model design preclude this assessment.

[34] Other life cycle analysis tools identified include the PaLATE and WARM models. Similar analyses of beneficial use of fly ash using these models are presented in Appendix C.

[35] The BEES model is accessible at: http://www.bfrl.nist.gov/oae/software/bees.html.

- Suspended matter in effluent (g)
- Biochemical oxygen demand in effluent (g)
- Mercury in effluent (g)
- Lead in effluent (g)
- Selenium in effluent (g)
- Potential human health impacts (g toluene equivalent)
- Nonhazardous end-of-life waste (kg)

Transport distances are important factors in the calculation of environmental impacts associated with the use of fly ash in concrete. Accordingly, BEES allows the user to specify one of three distances for the transport of the finished concrete product to the construction site. The user cannot modify distances for the transport of raw materials to the concrete plant.

Methodology

Our analysis is designed to explore the feasibility of estimating the benefits of fly ash use through existing models and data. As an example of the LCA approach, we assess the environmental benefits of using fly ash to offset virgin cement inputs in two different concrete applications: a structural building product and a pavement. For purposes of this analysis, we represent use of fly ash in a concrete pavement application with BEES product data for concrete parking lot pavement with a 3KSI compressive strength.[36]

The benefits of fly ash use are measured as the difference in environmental impacts between a baseline scenario and a beneficial use scenario. In the baseline scenario, one cubic yard of concrete pavement is produced using 100 percent Portland cement. In the beneficial use scenario, one cubic yard of concrete pavement is produced using 20 percent fly ash in place of a portion of virgin Portland cement. Depending on the mix design of the product, however, these benefits may reflect different quantities of fly ash. We, therefore, normalize these benefits by expressing them in terms of one ton of fly ash used in concrete pavement. To translate benefits from a cubic yard concrete basis to a metric ton fly ash basis, we divide the benefits by the quantity of fly ash in one cubic yard of the product. To illustrate this methodology, we present a sample calculation of water use reductions resulting from the substitution of one ton of fly ash for Portland cement in concrete pavement (see Exhibit 7).

[36] A compressive strength of 3 KSI indicates that the concrete pavement is capable of supporting 3,000 pounds per square inch of cross-sectional area.

EXHIBIT 7 EXAMPLE CALCULATION OF IMPACT METRIC FOR WATER USAGE RELATED TO FLY ASH SUBSTITUTION IN CONCRETE

	CALCULATION	3 KSI CONCRETE PAVEMENT	NOTE/SOURCES
IMPACTS PER CUBIC YARD CONCRETE			
100% Portland cement	[a]	1218 liters per cubic yard of concrete	Water use for concrete pavement is reported in BEES data file G2022A. BEES assumes a 20-mile transport distance. Pavement values converted from per square foot to cubic yard basis. BEES Version 3.0 Performance Data.
20% fly ash	[b]	1186 liters per cubic yard of concrete	Water use for concrete pavement is reported in BEES data file G2022A. BEES assumes a 20-mile transport distance. Pavement values converted from per square foot to cubic yard basis. BEES Version 3.0 Performance Data.
Incremental benefit	[c]=[a]-[b]	32 liters per cubic yard of concrete	Represents avoided water use, in liters per cubic yard of concrete product substituting 20% fly ash for Portland cement.
IMPACTS PER TON FLY ASH			
lbs cement/yd^3 concrete	[d]	376 lbs cement/cubic yard of concrete	Represents proportion of cubic yard of concrete made up of cementitious material, given a mix-design or constituent density. Barbara C. Lipiatt, "BEES 3.0 Technical Manual and User Guide," p. 40.
% fly ash substitution	[e]	20%	Twenty percent of cementitious material is replaced with fly ash.
lbs/ton	[f]	2000 lbs/ton	Conversion factor for pounds to tons.
MT fly ash/yd^3 concrete	[g]=[d]*[e]/[f]	0.038 tons fly ash/yd^3 of concrete	Conversion of quantity of fly ash in one cubic yard of concrete from pounds to tons.
unit impact	[h]=[c]/[g]	942 liters per metric ton of fly ash substituted for cement	Represent unit impact values for water (in liters), based on substitution of one ton fly ash in a concrete pavement.

The process outlined in Exhibit 7 is repeated for each of the environmental metrics listed above using environmental performance data reported in BEES. For each environmental metric, this yields an estimate of the benefit of one ton of fly ash replacing Portland cement in concrete parking lot pavement. These values can also be used to estimate the benefits of attaining EPA's goal for beneficial use of fly ash in concrete (i.e., 18.6 million tons by 2011). Extrapolated benefits are calculated by multiplying the benefits for use of one ton of fly ash in each product by 18.6 million tons.

Results

Exhibit 8 presents the results of the BEES analysis for each environmental metric, as well as an extrapolation of these results to attainment of EPA's beneficial use goal for CCPs.

EXHIBIT 8 LIFECYCLE ANALYSIS OF POTENTIAL IMPACTS OF PARTIAL FLY ASH SUBSTITUTION IN CONCRETE PARKING LOT PAVEMENT

	BASELINE SCENARIO[a]	BENEFICIAL USE SCENARIO[b]	DIFFERENCE[c]	FLY ASH UNIT IMPACT (PER TON FLY ASH)[d]	EXTRAPOLATED TO 2011 RCC CCP BENEFICIAL USE GOAL (18.6 MILLION TONS)[e]
ENERGY USE					
RENEWABLE ENERGY (MJ)	79	75	4	145	2,699,414,043
NONRENEWABLE ENERGY (MJ)	5,543	5,147	396	14,048	261,290,029,787
TOTAL PRIMARY ENERGY (MJ)	5,624	5,223	400	14,197	264,057,472,340
TOTAL PRIMARY ENERGY (US$)[f]	$155	$144	$11	$390	$7,261,580,489
WATER USE					
TOTAL WATER USE (L)	1,218	1,186	32	1,139	21,181,442,553
TOTAL WATER USE (US$)[g]	$9	$9	$0.23	$8	$153,876,296
ATMOSPHERIC EMISSIONS					
CO_2 (G)	531,113	471,313	59,800	2,120,553	39,442,289,361,702
METHANE (G)	563	512	51	1,798	33,447,944,681
CO (G)	825	770	56	1,978	36,792,382,979
NOX (G)	2,363	2,184	180	6,367	118,426,595,745
SOX (G)	1,371	1,227	144	5,102	94,905,114,894
PARTICULATES (G)	10,164	10,000	164	5,817	108,204,510,638
HG (G)	0.020	0.017	0.004	0.128	2,383,277
PB (G)	0.051	0.001	0.050	2	1,741,637
WATERBORNE WASTES					
SUSPENDED MATTER (G)	1.446	1.422	0.024	1	865,493,617
B.O.D (G)	0.318	0.313	0.005	0.190	190,586,681
MERCURY (G)	0	0	0	0	0
LEAD (G)	0	0	0	0	0
SELENIUM (G)	0	0	0	0	0
HUMAN HEALTH (G TOLUENE)	35,532,000	34,074,000	1,458,000	51,702,128	961,659,574,468,085
END OF LIFE WASTE (KG)	3,574	3,574	0	0	0

Notes:
a. The baseline scenario reflects a 100% Portland cement concrete mix-design.
b. The beneficial use scenario reflects a concrete mix design in which 20% of cement is replaced with fly ash.
c. The difference between the baseline and beneficial use scenarios represents the benefits associated with 0.028 tons fly ash in a concrete parking lot pavement.
d. Fly ash unit impacts are calculated by dividing the benefits in the "Difference" column by 0.028 tons fly ash.
e. We extrapolate the environmental benefits of using 1 ton fly ash in concrete pavement to the use of 18.6 million tons of fly ash in concrete (i.e. EPA's 2011 goal for beneficial use of fly ash in concrete). Extrapolated benefits are calculated by multiplying the fly ash unit impacts by 18.6 million.
f. The average cost of electricity in 2006 is $0.0275/MJ (Federal Register, February 27, 2006, accessed at: http://www.npga.org/14a/pages/index.cfm?pageid=914).
g. The average cost per gallon of water in 2005 was $0.00234/gal (NUS Consulting Group, accessed at: https://www.energyvortex.com/files/NUS_quick_click.pdf).

As shown in Exhibit 8, substitution of 20 percent fly ash for Portland cement in a parking lot pavement application yields positive environmental benefits. These benefits are achieved primarily as a result of avoided extraction of raw materials for cement production. In this analysis, the use of 18.6 million tons of fly ash in concrete pavement results in energy savings of approximately 264 billion megajoules. The value of this avoided energy consumption in dollar terms is approximately $7.3 billion.

Reductions in CO_2 emissions are closely related to reduced energy consumption. In this analysis, partial substitution of virgin Portland cement with fly ash results in approximately 34.9 million megagrams of avoided CO_2 emissions (extrapolated).

BEES also estimates 21.2 billion liters in avoided water consumption (extrapolated), valued at approximately $154 million. Other environmental benefits presented in Exhibit 8 include reduced emissions of criteria pollutants such as NO_X (118 billion g), SO_X (95 billion g), and particulates (108 billion g), as well as reductions in waterborne waste such as suspended matter (866 million g) and biochemical oxygen demand (191 million g). We do not calculate these benefits in dollar terms as monetizing involves complex valuation procedures.

In addition to environmental benefits, BEES also reports human health benefits when fly ash replaces a portion of cement in a concrete pavement application. Extrapolated human health benefits are calculated as 961.7 trillion grams of avoided toluene equivalent.[37] It is important to note that the pathways for human exposure to fly ash are comparable to those for Portland cement dust and pose similar human health risks.[38] These pathways include:

[37] Toluene equivalents represent a combined measure of cancer and non-cancer human health effects in BEES. BEES converts cancer effects, which are measured in benzene equivalents, to toluene equivalents using a ratio of threshold levels for toluene and benzene. Similarly, other LCA-based models, such as the PaLATE model presented in Appendix C, provide human health benefit as Human Toxicity Potentials (HTP). HTP is a risk screening approach that uses a calculated index reflecting the potential harm of a unit of chemical released into the environment. HTPs may provide a method for quantifying life cycle changes in human health impacts in the absence of a more comprehensive risk assessment. Scoring is based on both the inherent toxicity of a compound and its potential dose. Separate HTPs exist for each chemical by exposure route, including air, water, and soil. See Edgar G. Hertwich, Sarah F. Mateles, William S. Pease, Thomas E. McKone (2001) *Environmental Toxicology and Chemistry* 20(4):928-939 for more information.

[38] Both Portland cement and fly ash must be kept in silos until mixed. Therefore the risk of exposure to both materials is similar. Personal communication with Dave Goss, American Coal Ash Association, May 2006.

- **Inhalation.** Air inhalation of dust is primarily a worker safety issue. Workers involved with dry ash handling, concrete grinding, or demolition activities can come into contact with fugitive dust containing fly ash. An EPRI study to determine potential health effects of workers in frequent contact with fly ash concluded that routine operating activities did not produce hazardous exposures. In addition, occupational health records for these types of workers do not show a higher incidence of respiratory problems than those of power plant workers who do not work as closely with fly ash.[39]

- **Ingestion.** Generally, when fly ash is used in concrete for building roads and bridges, trace elements are bound (encapsulated) in the matrix of the concrete and are very stable. Leaching of these constituents into ground or surface water, for all practical purposes, does not occur.[40]

- **Skin Contact.** Power plant workers and people involved in producing cement, concrete, or other ash-based products can have skin contact with coal fly ash. In highway applications, skin contact is likely limited to construction workers working with dry ash. While proper handling and construction safety practices can control most contact with fly ash, if contact does occur, coal ash can cause skin irritation or contact dermatitis.[41]

Limitations and Assumptions

Although the BEES analysis provides a useful example of the benefits that can be achieved through beneficial reuse of fly ash in concrete, it is important to recognize some of the key limitations and assumptions of the work to date:

- The BEES model may over or under estimate the national impacts of using fly ash in concrete construction projects since site-specific environmental conditions and proximity to sources of fly ash may affect the resulting benefits and influence the net effect of choosing fly ash over Portland cement.

- BEES assumes round-trip distances for the transport of concrete raw materials to the ready-mix plant of 60 miles for Portland cement and fly ash and 50 miles for aggregate. The user cannot adjust these transport distances. This analysis also assumes the minimum possible transport distances for the finished concrete products to the construction site. This transport distance for ready-mix concrete for a pavement application is 50 miles.

- BEES environmental results are reported in physical quantities (e.g., MJ energy, liters water, g CO, g NO, g Hg, etc.), not in monetized terms.

ADDITIONAL BENEFIT: AVOIDED LANDFILL DISPOSAL COSTS

In addition to the lifecycle benefits estimated above using the BEES model, we also examine the benefit of avoided landfill disposal from beneficial use of CCPs in 2005.

[39] US EPA, "Using Coal Ash in Highway Construction: A Guide to Benefits and Impacts," EPA-530-K-05-002, April 2005.

[40] US EPA, "Using Coal Ash in Highway Construction: A Guide to Benefits and Impacts," EPA-530-K-05-002, April 2005.

[41] US EPA, "Using Coal Ash in Highway Construction: A Guide to Benefits and Impacts," EPA-530-K-05-002, April 2005.

Given that CCP landfill disposal costs range from $5 per ton to $45 per ton, the beneficial use of 50 million tons of CCPs results in avoided disposal costs ranging from $250 million to $2.3 billion.[42] While this estimate does not represent a net savings (i.e., because alternative uses of C&D debris may impose some management costs) it provides an initial indicator of the magnitude of savings associated with beneficial use.

FACTORS AFFECTING BENEFICIAL USE AND HYPOTHETICAL SCENARIOS FOR ADDRESSING THEM

As indicated by the preceding examinations of life cycle impacts, significant environmental benefits may be associated with increased beneficial use of CCPs. Several factors, however, affect increased beneficial use of these materials. Exhibit 10 outlines several of these factors and presents hypothetical scenarios that might address them. It is important to note that the hypothetical scenarios described below are intended only to illustrate possible conditions for increasing the beneficial use of CCPs; they do not represent specific policy recommendations.

EXHIBIT 10 LIMITING FACTORS TO INCREASED BENEFICIAL USE OF CCPs

FACTOR TYPE	LIMITING FACTORS OF BENEFICIAL USE	HYPOTHETICAL SCENARIOS
Economic	Transportation costs generally limit the shipment of CCPs to within a 50-mile radius of power plants. In some cases, the cost of transport to the end user may be prohibitively expensive.	Implementation of strategic actions to create incentives to increase beneficial use by shifting the economic drivers (i.e., cost of materials) in favor of CCPs. Potential incentives could include tax credits for the use of CCPs, raising CCP landfill disposal tipping fees, or streamlining the permitting process for facilities that use CCPs near coal combustion plants (e.g., FGD gypsum plants).
	In some parts of the country and for certain use applications, the cost of virgin materials may be cheaper than CCPs.	
	Inexpensive landfill disposal can limit incentive to sell rather than dispose of CCPs.	
Institutional	National standards organizations have promulgated specifications that limit or disallow the use of CCPs in some construction applications because of quality and performance concerns.	State DOTs rely on consensus standards for guidance and generally accept the use of fly ash in concrete. DOT projects can be used to demonstrate the performance of CCPs in geotechnical applications.
	The implementation of the U.S. Clean Air Mercury Rule (CAMR) may result in altering the chemical properties of fly ash, rendering it unmarketable for beneficial use. Similar impacts may also occur for fly ash containing higher levels of unburned carbon or other components resulting from installation of low-NOx burners at coal-based power plants.	Establishment of a research and development infrastructure to address the technical limiting factors to CCP use. Provide technical assistance to utilities using low-NOx burners to identify and implement cost-effective process modifications or new equipment to reduce the carbon content of fly ash.

[42] To ensure that this landfill disposal rates range is reasonable, we examined multiples sources including EPRI (Electric Power Research Institute (EPRI). 2006. "Coal Combustion Product Use." accessed at: http://www.epri.com/Portfolio/product.aspx?id=2065&area=50; Electric Perspectives. 2003. "The Outlook for CCPs." July/August. accessed at: http://www.uswag.org/ccpoutlk.pdf; and Southeastern Public Service Authority. 2006. "Business Services: Tipping Fees." Accessed at: http://www.spsa.com/business/bus-tipping.asp.

FACTOR TYPE	LIMITING FACTORS OF BENEFICIAL USE	HYPOTHETICAL SCENARIOS
Technical	Lack of consistency and quality in the production of fly ash have limited use in the high-value ready-mix concrete market. Often, the priority at a coal-fired power plant is on producing electricity, not ash. A change in the combustion process, such as the type of coal burned, results in a change in ash quality, making it difficult to produce a consistent product.	Facilitate formal training programs to teach plant operators about the value of producing consistent-quality fly ash.
Educational	While quality and consistency of fly ash are legitimate concerns of end-users, in some cases, negative perceptions toward CCP use are unwarranted. Negative perceptions can often be attributed to a single experience using CCPs in a project that failed, even if CCPs were not the cause of the failure. For example, at one time, the Austin concrete market almost turned to an all-cement market because of one misuse resulting from a lack of education about the material.	Dissemination of objective, scientific material to educate potential end users. (EPA is currently addressing this through C2P2).

Sources:
1. U.S. Department of Energy, National Energy Technology Laboratory, "General Summary of State Regulations," accessed at: http://www.netl.doe.gov/E&WR/cub/states/select_state.html.
2. Energy and Environmental Research Center, "Barriers to the Increased Utilization of Coal Combustion/Desulfurization By-Products by Government and Commercial Sectors--Update 1998," EERC Topical Report DE-FC21-93MC-30097--79, July 1999.
3. American Coal Ash Association, "Frequently Asked Questions," accessed at: http://www.acaa-usa.org/FAQ.htm.
4. Schwartz, Karen D. "The Outlook for CCPs," *Electric Perspectives*, July/August 2003.
5. Energy & Environmental Research Center, University of North Dakota, "Review of Florida Regulations, Standards, and Practices Related to the Use of Coal Combustion Products: Final Report," April 2006, accessed at: http://www.undeerc.org/carrc/Assets/TB-FLStateReviewFinal.pdf.
6. Energy & Environmental Research Center, University of North Dakota, "Review of Texas Regulations, Standards, and Practices Related to the Use of Coal Combustion Products: Final Report," January 2005, accessed at: http://www.undeerc.org/carrc/Assets/TXStateReviewFinalReport.pdf.

As shown in Exhibit 10, some limiting factors of increased use of CCPs require changes to the basic economics of beneficial use. However, a number of factors could be addressed through provision of better information to generators and potential users of CCPs. Consequently, scenarios exist to facilitate the exchange of information between generators, end-users and regulatory agencies in order to build larger markets for CCPs.

CONCLUSIONS AND ADDITIONAL CONSIDERATIONS

CCPs are an area of focus of EPA's Resource Conservation Challenge, an initiative that identifies and encourages innovative, flexible ways to conserve natural resources and energy. CCPs are a large material stream targeted by the RCC for an increase in beneficial use. Based on current estimates, the coal combustion industy generates 123 million tons of CCPs annually. Of these, approximately 58 percent by volume consist of fly ash (71 million tons). Other notable CCPs include FGD material, bottom ash, and boiler slag.

CCPs are widely used in a range of applications, including concrete, wallboard, and structural fill. Currently, 40 percent of all CCPs are beneficially used, with boiler slag and FGD gypsum having the highest percentage of beneficial use (97 and 77 percent, respectively). Economic factors, that may affect both sellers (generators) and purchasers (end-users) of CCPs, may prove to be the most significant limitations to increasing the beneficial use of CCPs. These factors include low landfill disposal costs, transport costs, potential storage costs, inexpensive virgin material alternatives, and the ability of CCPs to meet adequate technical specifications. In addition, concerns and perceptions regarding the safety and human health risks associated with the use of CCPs may delay or prevent the beneficial use of CCPs in some contexts.

It may be possible to address many of these factors through a greater exchange of technical and cost information between coal-fired power plants, end-users, and regulatory agencies to build larger markets for CCPs. To this end, EPA will continue to provide state agencies that establish the procedures for the beneficial use of CCPs, with the latest information about CCP applications and research.

Based on a limited assessment of the life cycle benefits of fly ash use in concrete applications, beneficial use results in environmental benefits. These include, for example, energy savings, water savings, reduced air emissions (e.g., carbon dioxide, sulfur dioxide, and particulates), and potentially avoided human health impacts. Exhibit 11 summarizes the key benefits identified in this report.

EXHIBIT 11: SUMMARY OF KEY BENEFITS

	BENEFITS OF BENEFICIALLY USING FLY ASH IN CONCRETE EXTRAPOLATED TO THE RCC GOAL (18.6 MILLION TONS)
Avoided energy consumption	264.1 billion MJ
Avoided energy costs	$7.3 billion
Avoided water consumption	153 million gallons
Avoided water costs ($)	$154 million
Avoided CO_2 emissions	39 million metric tons
Avoided SO_X emissions	95,000 metric tons
Avoided NO_X emissions	118,000 metric tons
Potentially avoided human health impacts	962 million metric tons of toluene equivalent
Avoided disposal costs	$250 million to $2.3 billion

Our initial analysis also suggests that environmental benefits associated with the beneficial use of CCPs are likely for other applications (e.g., gypsum wallboard and structural fill). In the future, EPA may wish to consider several additional efforts for further analysis of beneficial use of CCPs, including:

- **Incorporation of changes in product attributes into the benefits estimates.** In many cases, it appears that beneficially using CCPs in applications actually enhances the utility of these products. For example, fly ash has been shown to increase the strength and durability of concrete. The benefits metrics presented in this report do not currently adjust for these product enhancements. It may possible to develop measures that characterize the additional benefits gained through product improvements.

- **Analysis of additional CCP materials beyond fly ash in concrete.** Due to resource and data constraints, this report focuses the benefits assessment on the beneficial use of fly ash in concrete applications. To gain a more complete perspective on the benefits of the beneficial use of CCPs, it will be important to characterize the benefits of additional beneficial use scenarios and materials, including FDG gypsum, FGD wet material, bottom ash, boiler slag, and FBC ash.

- **Collection of specific information on EPA program design and dynamics.** The preliminary analysis outlined above does not incorporate a comprehensive understanding on how specific EPA programs are designed and targeted to improve the beneficial use rate of CCPs. This report provides an initial summary of available baseline information, but assessment of the specific impacts of EPA programs in the context of program evaluation will require more detailed data on program activities and on the specific materials and practices that are targeted for change.

- **Attribution of benefits to specific EPA programs.** Particularly in the case of voluntary programs, such as C2P2, it is difficult to attribute changes in behavior to specific EPA activities. Changes in recycling or source reduction may be due to outside forces (i.e., market dynamics), multiple government programs, or combination of both. Data related to specific EPA activities may clarify specific impacts, particularly in the case of project-oriented programs such as priority chemicals. For other programs, it may be necessary to start with the assumption that all costs and all benefits are related to EPA activities, and adjust that assumption as programs mature and data become available.

REFERENCES

ACAA (American Coal Ash Association). 2006a. Dave Goss. Personal Communication. March 2006.

ACAA (American Coal Ash Association). 2006b. Dave Goss. Personal Communication. April 2006.

ACAA (American Coal Ash Association). 2006c. Dave Goss. Personal Communication. May 2006.

ACAA (American Coal Ash Association). undated. Accessed at: www.acaa-usa.org.

American Coal Foundation. 2003a. "All About Coal: Fast Facts About Coal." Accessed at: http://www.teachcoal.org/aboutcoal/articles/fastfacts.html.

American Coal Foundation. 2003b. "Coal's Past Present and Future." Accessed at: http://www.teachcoal.org/aboutcoal/articles/coalppf.html.

Apul, Define. University of Toledo. "2nd Quarterly Report for EPA-OSWER Innovation Pilot FY05: Development of a Beneficial Reuse Tool for Managing Industrial Byproduct," 2005.

Caltrans (California Department of Transportation). 2006. Tom Pyle. Personal Communication. November 2006.

Center for Energy and Economic Development. undated. "Growing Demand." Accessed at: http://www.ceednet.org/ceed/index.cfm?cid=7500,7582.

DOT (U.S. Department of Transportation). 2006. John D'Angelo. Personal Communication. March 2006.

Edgar G. Hertwich, Sarah F. Mateles, William S. Pease, Thomas E. McKone. 2001. *Environmental Toxicology and Chemistry* 20(4):928-939.

Electric Power Research Institute. 1999. Environmental Focus: Flue Gas Desulfurization By-Products. BR-114239.

Electric Power Research Institute. 2006. "Coal Combustion Product Use." Accessed at: http://www.epri.com/Portfolio/product.aspx?id=2065&area=50.

Energy & Environmental Research Center. 2006. "Review of Florida Regulations, Standards, and Practices Related to the Use of Coal Combustion Products: Final Report." University of North Dakota. April 2006. Accessed at: http://www.undeerc.org/carrc/Assets/TB-FLStateReviewFinal.pdf.

EPA. (U.S. Environmental Protection Agency). 1999. Report to Congress: Wastes from the Combustion of Fossil Fuels. Vol. II. EPA-530-R-99-010, March 1999.

EPA. (U.S. Environmental Protection Agency). 2003. "Underground Storage Tanks (UST) Cleanup & Resource Conservation & Recovery Act (RCRA) Subtitle C

Program Benefits, Costs, & Impacts (BCI) Assessments: An SAB Advisory." EPA-SAB-EC-ADV-03-001

EPA. (U.S. Environmental Protection Agency). 2005. Using Coal Ash in Highway Construction: A Guide to Benefits and Impacts. EPA-530-K-05-002, April 2005.

EPA. (U.S. Environmental Protection Agency). 2006. “About C2P2.” Accessed at: http://www.epa.gov/epaoswer/osw/conserve/c2p2/about/about.htm.

EPA. (U.S. Environmental Protection Agency). 2006. “Boiler Slag.” Accessed at: http://www.epa.gov/epaoswer/osw/conserve/c2p2/about/about.htm.

EPA. (U.S. Environmental Protection Agency). 2006."Advisory on EPA's Superfund Benefits Analysis." EPA-SAB-ADV-06-002.

Glenn, J., Goss, D. and J. Sager. undated. “C2P2--Partnership Innovation.”

Hendrickson, Chris, Lester Lave, and H. Scott Matthews. 2006. *Environmental Life Cycle Assessment of Goods and Services*, Resources for the Future: Washington, DC, 2006.

Hassett, David J., Debra F. Pflughoeft-Hassett, Dennis L. Laudal, and John H. Pavlish. 1999. Mercury Release from Coal Combustion ByProducts to the Environment.

Portland Cement Association. 2006. “FAQ: Cement Supply Shortage.” Accessed at: http://www.cement.org/pca/shortageQA.asp.

Price, Jason and Mark Ewen, Industrial Economics, Inc. Memorandum to Lyn Luben, EPA, “Impact of CAIR and CAMR on the Quantity and Quality of Coal Combustion Fly Ash Generated by Affected Facilities.” December 1, 2006.

Wisconsin Department of Natural Resources. 2006. Bizhan Sheikholeslami. November 2006.

APPENDIX A

EXHIBIT A-1 KEY BENEFICIAL USE APPLICATIONS FOR CCPS (2005)

BENEFICIAL USE APPLICATION AND INDUSTRY	FLY ASH	BOTTOM ASH	FGD GYPSUM	FGD - WET	FGD - DRY	BOILER SLAG	PRODUCT SUBSTITUTES
Concrete	14,989,958	1,020,659	328,752	0	13,965	0	Cement, Silica fume, Furnace slag
Cement additive	2,834,476	939,667	397,743	782	0	42,566	Clay, Soil, Shale, Gypsum
Flowable fill	88,549	0	0	0	9,673	0	Soil, Sand, Gravel, Cement
Structural fill	5,710,749	2,321,140	0	0	2,666	175,144	Sand, Gravel, Soil, Aggregate
Road base	205,032	1,056,660	0	0	0	300	Cement, Lime, Aggregate
Soil stabilizer	715,996	205,322	0	0	1,535	0	Cement, Lime, Aggregate
Mineral filler in asphalt	62,546	21,583	0	0	0	56,709	Sand
Snow and ice control	591	531,549	0	0	0	15,401	Sand
Blasting grit	0	89,109	0	0	0	1,544,298	Sand
Mine reclamation	626,428	46,604	0	245,471	112,100	31,540	Soil
Wallboard	0	0	8,178,079	0	0	0	Natural gypsum
Waste stabilization	2,657,046	42,353	0	0	0	0	Cement, Lime, Cement kiln dust
Agricultural soil amendment	23,856	7,670	361,644	3,312	19,259	0	Liming agents
Manufactured aggregate	180,275	692,501	0	0	0	0	Sand, gravel, aggregate
Miscellaneous/other	1,022,952	567,155	2,147	436,619	0	24,851	
CCP Category Use Totals	29,118,454	7,541,972	9,268,365	689,184	159,198	1,890,809	
CCP Utilization Rate	41%	43%	77%	4%	11%	97%	

Sources:
1. American Coal Ash Association. “2005 Coal Combustion Product (CCP) Production and Use Survey,” accessed at: http://www.acaa-usa.org/PDF/2005_CCP_Production_and_Use_Figures_Released_by_ACAA.pdf.
2. Western Region Ash Group, “Applications and Competing Materials, Coal Combustion Byproducts,” accessed at: http://www.wrashg.org/compmat.htm.

APPENDIX B

USE OF LIFE CYCLE ANALYSIS IN AN EVALUATION OF ECONOMIC BENEFITS

Life cycle assessment (LCA) inventory analyses of the type presented in this report deliver incremental changes in physical inputs, outputs, and energy arising from management or regulatory changes to an industrial production process. This discussion addressing the following issues: how does LCA relate to economic analysis of benefits, and how are economic impacts derived from changes in "physical inventory," such as energy use and alternative waste streams?

RELATIONSHIP LCA AND ECONOMIC ANALYSIS OF BENEFITS

LCA is a performance assessment tool – a method to depict physical outcomes that can be used to assess impacts and measure progress over time. And because LCA is a systems approach to assessment, it offers significant improvement over less comprehensive techniques. However, in economic terms, LCA is only one component of a true analysis of benefits – albeit a central component.

Consider the architecture of an economic benefit assessment. At the "front end" lies a set of economic drivers that determine technologies and practices employed by industry. These drivers include raw material prices, other input costs (including transport), competitive factors, regulation, technology, and taxes. EPA programs such as RCC work to facilitate changes in the economic drivers of waste generation, handling, and disposal (e.g., a change in tipping fees, tighter permit requirements on landfills, benefits to participation in beneficial use programs, etc.). Changes in these economic drivers can be expected to lead to changes in the physical system of production. In other words, the physical system and its outputs are properly thought of as the end product of a set of economic incentives (prices) and constraints (technology).

LCA depicts production as a *system* of sometimes reinforcing, sometimes counteracting physical outcomes. In particular, it allows the analyst to predict the *incremental* physical consequences of a change in disposal practices, technology, or price incentives. Any change in the physical system leads to a corresponding cascade of system changes – as inputs are substituted, exposure pathways are changed, and technology adapts. LCA produces the net result of these various changes and thus the true, incremental effect on physical outputs.[43]

Deriving an incremental physical effect from a complex system is difficult enough. As the agency seeks for performance measures to satisfy its GPRA and PART requirements LCA is a natural starting point. It demands systems thinking, properly views outcomes as changes to baseline conditions, identifies tradeoffs, and yields concrete, measurable metrics. LCA can tell us *who* and *what* will be affected by changes in industrial practice, and even *where* changes are likely to occur.

However, while LCA is a fundamental building block of benefit assessment, LCA does not itself yield the social benefits and costs of industrial change. To do that, we must apply economic valuation techniques to the physical outputs of LCA analysis.

[43] For example, the PaLATE model generates incremental effects on physical outputs arising from changes in roadway materials.

Why is economic assessment desirable? Because we don't really care about physical outcomes, we care about what those outcomes imply for human well-being. Another way of putting this is, how do we compare the "apples" of one change to the "oranges" of another?[44] Compare a given "small" physical gain in one waste to a "large" reduction in another. In physical terms, we might be tempted to say that the large gain outweighs the small loss. Of course, small physical changes can have large health and environmental consequences with large economic ramifications (think of the effect of radiation or toxics on health).

To understand how energy and raw materials use and emission of different kinds affect well-being we must make a set of additional "translations." A physical change in lead concentrations leads, via ecological and epidemiological processes, to changes in human exposure. Changes in exposure lead to morbidity and mortality effects. Morbidity and mortality effects have social benefits and costs.[45] Those benefits and costs are the ultimate goal of analysis. In another example, the effect of water consumption on well-being depends upon the location, timing, and quality of the water that is consumed. The value of that water depends on how it would otherwise be used – for human consumption, industrial uses, habitat support, irrigation, etc. LCA tells us little if anything about these relationships. Thus, LCA may tell us relatively little about the actual welfare effects of changes in industrial process.

Unfortunately, the translation of physical changes into economic outcomes is costly, difficult, and often controversial when applied to human health or environmental outcomes. As the report notes earlier, "we do not calculate these benefits in dollar terms as monetizing involves complex valuation procedures." Putting economic value on even a small set of physical impacts can be a significant and expensive proposition.

Accordingly, LCA should be regarded, not only as a necessary ingredient, but also as a practical alternative to real benefit assessment. While economic benefits are the ultimate performance measure, businesses and governments routinely rely on simpler – though imperfect – proxies to facilitate management and performance assessment. As proxies, LCA outputs are a legitimate and defensible compromise.

INVENTORY CHANGES AND WELFARE: THE TRANSLATION OF LCA OUTPUTS TO ECONOMIC IMPACTS

There are two basic steps that must be employed to translate LCA-generated inventories into social benefits. The first is the translation of LCA inventories into "final economic goods." The second is the valuation of those final goods.

Mapping LCA inventories into final economic goods

In general, changes in LCA physical inventories will generate a set of corresponding changes in other physical conditions relevant to human well-being. Even before economic valuation occurs, these follow-on physical implications must be assessed. For instance, to value changes in mercury releases it is important to know how increased

[44] Hendrickson, Lave, and Matthews (2006) ("A typical [Life Cycle Inventory] of air pollution results in estimates of conventional, hazardous, toxic, and greenhouse gas emissions to the air. Even focused on this small subset of environmental effects, it is unclear how to make sense fo the multiple outputs and further how to make a judgment as to tradeoffs or substitutions of pollutants among alternative designs."), 29.

[45] Some in the LCA community refer to this as an LCA impact analysis, as opposed to the preceeding LCA inventory analysis. Inventory analyses are those most commonly referred to as LCA. See Graedel and Allenby (1995).

mercury emissions interact with exposure pathways to affect body burdens and human health. An LCA inventory does not address this issue; an analysis of epidemiology and exposure is required. Similarly, hydrological analysis is required to determine how a reduction in water usage translates into water availability in different locations and at different times. Further, ecological analysis must be deployed to answer questions such as" what is the effect of greater water availability on species and habitats?" The point is that benefit assessment requires synthetic systems thinking of an order at least as great as the original LCA analysis.[46]

The goal of these biophysical and epidemiological translations is to translate LCA inventory results to outcomes with *direct* human impact – health effects or the availability of water in a particular stream at a particular time.

In the human health realm, toxic wastes or air quality burdens must be evaluated in terms of fate, transport, and deposition models. Human health models then translate depositions into human health impacts via epidemiological analysis (e.g., dose-response relationships). EPA is relatively sophisticated in its use of such models, owing to decades of experience with air quality regulation and the analysis of economic effects arising from air quality-related health assessments.

In the ecological realm, these kinds of translations are underdeveloped. The agency is aware of this – the conclusion has been drawn from several recent SAB reports, for example.[47] The analysis of ecological benefits is clarified by drawing distinctions ecosystem processes and functions and the "final" outcomes of those processes (denoted here as "final ecosystem goods." Ecosystem processes and functions are the biological, chemical, and physical interactions associated with ecological features such as surface water flows, habitat types, and species populations. These functions are the things described by biology, atmospheric science, hydrology, and so on.

Final ecosystem goods arise from these components and functions but are different: they are the aspects of the ecosystem that are *directly* valued by people. The benefits of nature include many forms of recreation, aesthetic enjoyment, commercial and subsistence harvests, damage avoidance, human health, and the intangible categories mentioned earlier. Final ecosystem goods are the aspects of nature used by society in order to enjoy those benefits.

Part of the above definition is particularly important: namely, that ecosystem services are "final." Final goods are the things people actually make choices about. For an angler, these end products include a particular lake or stream and perhaps a particular species population in that water body. The choices involved include which lake, what kind of fish, what kind of boat (if any) and tackle to use, and how much time spent getting to and from the site. Valuation is about choices (is one thing better than another) and choices are the only thing economists can use to establish economic value. Environmental benefit assessment places values on the things people and households make actual choices about – the "final goods" of nature. It is very important to emphasize that many other aspects of

[46] For an example of a full social cost & benefit analysis see Krupnick and Burtraw (1997).

[47] For example, this conclusion has been drawn from several recent SAB reports, including EPA-SAB. 2003. "Underground Storage Tanks (UST) Cleanup & Resource Conservation & Recovery Act (RCRA) Subtitle C Program Benefits, Costs, & Impacts (BCI) Assessments: An SAB Advisory." (EPA-SAB-EC-ADV-03-001) and "Advisory on EPA's Superfund Benefits Analysis." (EPA-SAB-ADV-06-002). In addition, the SAB Committee on Valuing the Protection of Ecological Systems and Services is currently examining methods for addressing these limitations.

nature are valuable, but not capable of being valued in an economic sense – because they are not subject to social or individual choices.

Ecosystem production functions are the relationships that translate LCA inventory changes into final ecosystem goods. One characteristic of these production functions is particularly worthy of note: ecological production functions are dependent upon space and landscape. Location- and scale-specificity are core characteristics of modern ecology. For example, the quality of a habitat asset can be highly dependent on the quality and spatial configuration of surrounding land uses. The ability of areas to serve as migratory pathways and forage areas typically depends on landscape conditions over an area larger that habitats relied upon directly by the migratory species. The contiguity of natural land cover patches has been shown for many species to be an indicator of habitat quality and potential species resilience. Hydrological analysis is yet another field that has long recognized the importance of relationships between landscape features. The nature of surface water flows, aquifer structures, and surface-groundwater interactions are dependent upon linked physical relationships across the landscape.

For OSW to move toward measurement of ecosystem impacts arising from beneficial reuse, or any other change in waste management practices, the ability to translate LCA inventory changes into final ecosystem good changes requires the development of spatial ecological modeling. Space and scale are important to the valuation of final ecosystem goods, as well.

Assigning value to changes in final ecological goods

The value of an ecosystem good is typically location-dependent. The value of a car is not closely related to whether it is located in California or New Jersey. This is not the case with ecological goods. The benefits of damage mitigation, aesthetic enjoyment, and recreational and health improvements depend on where—and when—ecosystem services arise relative to complementary inputs and substitutes. Also, the ecological asset interactions that enhance or degrade service flows are highly landscape-dependent. Accordingly, it is necessary to spatially define “service areas.” An unfortunate reality is that these will be different for every identified ecosystem service. Boundaries are needed to define the likely users of a service, areas in which access to a service is possible, and the area over which services might be scarce or have substitutes. This issue is well known in environmental economics (Smith and Kopp 1996). For example, a key methodological issue in any econometric recreational benefits study is the determination of the appropriate choice set facing recreators.

While market prices can be assumed to be largely constant within a single market, there is no arbitrage to ensure this condition for the implicit prices of environmental resources. Also, many ecological services are best thought of as differentiated goods with important place-based quality differences. As noted earlier, the biophysical characteristics of ecosystems are highly landscape-dependent. The same is true of ecological services’ social benefits. Accordingly, willingness to pay for ecological services is best represented by a hedonic price function, not a single price.

An intermediate step: benefit indicators as an alternative to full valuation

The spatial factors that affect ecosystem goods' value create a problem for analysts. Benefit estimates from one study in one location cannot be transferred to other sites. In practical terms, this means that ecosystem valuation is expensive, time-consuming, and difficult. Problem-specific valuation will be impractical for most regulatory applications.

In this context, one alternative to full scale valuation is the use of "benefit indicators" (Boyd 2004, Boyd and Wainger 2002). The benefits of a given ecosystem good are affected by the following: the ecosystem feature's scarcity, natural and built substitutes, complementary inputs, and the number of people in proximity to it. All of these can and should be measured spatially. Benefit indicators are map-able, countable landscape features that affect the value of a particular ecosystem good. Benefit indicators are an input to a wide variety of tradeoff analysis approaches, but do not themselves make or calculate the results of such tradeoffs. First, they can be used as ends in themselves as regulatory or planning performance measures. Second, they can be used as part of public processes designed to elicit public preferences over environmental and economic options – as in mediated modeling exercises or more informal political derivations. Benefit indicators are a potentially powerful complement to group decision processes. Third, they can be used as *inputs* to economic and econometric methods such as benefit transfer, or stated preference models. In the former, they can be used to calibrate the transfer function. In the latter case, they can be used to develop alternative choice scenarios.

REFERENCES

Boyd, James, "What's Nature Worth? Using Indicators to Open the Black Box of Ecological Valuation," *Resources*, 2004.

Boyd, James and Lisa Wainger, "Landscape Indicators of Ecosystem Service Benefits," 84 *American Journal of Agricultural Economics*, 2002.

Graedel, T.E., and B.R. Allenby, *Industrial Ecology*, Prentice Hall: Englewood Cliffs NJ, 1995.

Hendrickson, Chris, Lester Lave, and H. Scott Matthews, *Environmental Life Cycle Assessment of Goods and Services*, Resources for the Future: Washington, DC, 2006.

Krupnick, Alan and Dallas Burtraw, "Social Costs of Electricity: Do the Numbers Add Up?" *Resources and Energy* 18:4, 1997, 423-466.

Porter, Richard, *The Economics of Waste*, Resources for the Future: Washington, DC, 2002.

Portney, Paul, "The Price Is Right: Making Use of Lice Cycle Analyses," *Issues in Science and Technology*, 10: 2 Winter, 1993, 69-75.

Smith, V. Kerry, and Ray Kopp, *Valuing Natural Assets: The Economics of Natural Resource Damage Assessment*, (Resources for the Future: Washington, DC, 1996.

APPENDIX C

ANALYSIS OF BENEFITS USING ALTERNATE LIFE CYCLE MODELS

In the main body of this report, we present an analysis of the life cycle benefits of substituting fly ash for Portland cement in concrete using the BEES model. Two additional life cycle tools for modeling beneficial use of fly ash in concrete are the PaLATE and WARM models. For comparative purposes, this appendix illustrates the benefits from beneficial use of fly ash in concrete that can be calculated using these models.

PALATE BENEFITS ASSESSMENT

PaLATE is an Excel-based tool for life cycle assessment (LCA) of environmental and human health effects of asphalt and concrete roads. PaLATE can be used to evaluate the relative impacts of using different materials, including virgin versus recycled materials, in the construction and maintenance of roadways. The model guides the user through a series of input worksheets gathering data on: the general design of the roadway, initial construction materials (recycled and virgin), material transportation distances and modes, maintenance materials and processes, as well as material transportation distances and modes, on-site construction equipment (e.g., asphalt paver), and off-site processing equipment (e.g., rock crusher). Based on these inputs, PaLATE calculates life cycle environmental and human health impacts, including:

- water consumption;
- energy use;
- air emissions (NO_x, SO_2, CO_2, PM_{10}, CO);
- toxic releases (Pb and Hg);
- RCRA hazardous waste generation; and
- human health implications (cancer and non-cancer Human Toxicity Potentials).

PaLATE reports these impacts separately for each lifecycle phase—initial construction and maintenance—as well as cumulatively. In addition, for each lifecycle phase, PaLATE reports the environmental and human health impacts associated with each process: materials production, materials transportation, and equipment processes.

The environmental and human health impacts of using recycled materials depend on the equipment used to recover and transport the materials. Energy use and air emissions impacts are based on typical productivity, fuel consumption, and engine size of the equipment associated with each recycling activity. The user is provided with default values and also given the choice of alternative values and/or equipment type for each activity.

Hauling distances are important factors in the calculation of environmental impacts associated with the use of recycled materials. Accordingly, PaLATE requires the user to specify the transportation mode and distances associated with each material, including recycled materials.

Methodology

As an example of the LCA approach in PaLATE, we assess the environmental and human health impacts of using fly ash to offset virgin cement inputs in 1,000 cubic yards of concrete mix for transportation applications. Benefits are measured as the difference in environmental and human health impacts between a baseline scenario and a beneficial use scenario.

In the baseline scenario, 1,000 cubic yards of concrete are produced using only virgin materials. The average concrete mixture contains 30 percent Portland cement, 30 percent water, and 70 percent aggregate on a volume-basis.[48] Applying these mix-specifications to 1,000 cubic yards of concrete yields the following mix-design quantities:

EXHIBIT 7 BASELINE SCENARIO: VIRGIN CONCRETE MIX-DESIGN ASSUMPTIONS

VOLUME CONCRETE ANALYZED	MIX-DESIGN PERCENTAGES	MIX-DESIGN VOLUMES
1,000 yd^3 concrete =	70% aggregate =	700 yd^3 aggregate
	15% Portland cement =	150 yd^3 Portland cement
	15% Water =	150 yd^3 water
TOTAL	**100% Concrete**	**1,000 yd^3 concrete**
Source: John D'Angelo, US Department of Transportation, March 2006.		

These mix-design volumes were entered as inputs in the first run of the PaLATE model, representing the baseline or virgin concrete scenario.

In the beneficial use scenario, 1,000 cubic yards of concrete are produced using fly ash in place of a portion of virgin Portland cement inputs. Fly ash can replace 15 to 30 percent or more of virgin Portland cement as a pozzolanic binder in concrete used in paving applications.[49] In this analysis, we use the mid-point of the range for fly ash input (22.5 percent). Replacing 22.5 percent of Portland cement inputs with fly ash in 1,000 cubic yards of concrete yields the following mix-design quantities:

EXHIBIT 8 BENEFICIAL USE SCENARIO: FLY ASH CONCRETE MIX-DESIGN ASSUMPTIONS

VOLUME CONCRETE ANALYZED	MIX-DESIGN PERCENTAGES	MIX-DESIGN VOLUMES
1,000 yd^3 concrete =	70% aggregate =	700 yd^3 aggregate
	11.6% Portland cement =	116 yd^3 Portland cement
	15% Water =	150 yd^3 water
	3.4% Fly ash =	34 yd^3 fly ash
TOTAL	**100% Concrete**	**1,000 yd^3 concrete**
Source: John D'Angelo, US Department of Transportation, March 2006.		

These mix-design volumes were entered as inputs in the second run of the PaLATE model, representing the beneficial use scenario.

[48] Personal communication, John D'Angelo, US Department of Transportation, March 2006.

[49] American Coal Ash Association, accessed at: www.acaa-usa.org.

This analysis evaluates only the environmental and human health impacts of the initial construction phase and its associated processes: materials production, materials transportation and equipment processes. Impacts from the maintenance phase are not evaluated. The analysis uses the same model default settings in both the baseline and beneficial use scenarios for pavement maintenance materials, processes, and equipment. Furthermore, both the baseline and beneficial use scenarios assume a 25-mile transport distance between the fly ash and Portland cement suppliers and the concrete manufacturing facility. The baseline scenario assumes transport of Portland cement via a cement-truck. Similarly, the beneficial use scenario assumes transport of fly ash via a cement-truck since fly ash is combined with cement at the ready-mix batch plant prior to delivery to the job site.[50]

Results

For both the baseline and beneficial use scenarios, PaLATE generates quantitative estimates of impacts for a suite of environmental factors. For each factor, the difference between the baseline and beneficial use scenario represents the environmental impact of reusing fly ash in concrete pavement. Where this difference is positive, the impact is an environmental benefit of fly ash use. Where the difference is negative, utilization of fly ash in concrete suggests a decline in environmental quality. After estimating impacts of the beneficial use of a fixed quantity of fly ash (34 cubic yards), the results of the PaLATE analysis for each environmental and human health factor may be extrapolated to estimate benefits of attaining EPA's goal for beneficial use of fly ash in concrete (18.6 million metric tons by 2011). It is important to note, however, that the PaLATE results relate specifically to concrete pavements and roads. Exhibit 9 below presents the results of the PaLATE analysis for each metric as well as an extrapolation of these outputs to attainment of EPA's beneficial use goal for fly ash (use 18.6 million tons fly ash in concrete by 2011).

EXHIBIT 9 PALATE LIFECYCLE ANALYSIS OF POTENTIAL IMPACTS OF PARTIAL FLY ASH SUBSTITUTION IN CONCRETE PAVEMENT

	BASELINE SCENARIO OUTPUTS	BENEFICIAL USE SCENARIO OUTPUTS	DIFFERENCE (IMPACT)	LIFECYCLE PHASE	EXTRAPOLATION TO 2011 FLY ASH USE GOAL[a]
Energy Consumption[b] (megajoules)	2,031,918 [$55,878]	1,869,680 [$51,416]	161,238 [$4,462]	Initial Construction	39.0 billion [$1.1 billion]
Water Consumption[c] (gallons)	839,000 [$1,963]	758,000 [$1,774]	81,000 [$189]	Initial Construction	19.4 billion [$45,409,513]
CO2 Emissions (megagrams)	142	131	11	Initial Construction	2,739,214
NOx Emissions (kilograms)	2,092	1,958	134	Initial Construction	32,271,654
PM10 Emissions (kilograms)	667	642	25	Initial Construction	6,033,256
SO2 Emissions (kilograms)	1,315	1,179	136	Initial Construction	32,766,710
CO Emissions (kilograms)	942	893	49	Initial Construction	11,691,821

[50] Personal communication with Dave Goss, American Coal Ash Association, May 2006.

	BASELINE SCENARIO OUTPUTS	BENEFICIAL USE SCENARIO OUTPUTS	DIFFERENCE (IMPACT)	LIFECYCLE PHASE	EXTRAPOLATION TO 2011 FLY ASH USE GOAL[a]
Hg Emissions (grams)	2.835	2.695	0.141	Initial Construction	33,716
Pb Emissions (grams)	181	168	13	Initial Construction	3,195,716
RCRA Hazardous Waste Generated (kilograms)	2,603	2,538	65	Initial Construction	15,693,520
Human Toxicity Potential (Cancer) [d]	47,317	47,924	-1.28% [e]	Initial Construction	-1.28% [e]
Human Toxicity Potential (Non-cancer) [d]	59,097,778	61,400,856	-3.90% [e]	Initial Construction	-3.90% [e]

Notes:

a. We extrapolate the results of our beneficial use scenario to the use of 18 million tons of fly ash in concrete (i.e. EPA's 2011 goal). To estimate these impacts, each of the figures calculated by the PaLATE model is multiplied by a scaling factor of 240,642. We calculate this scaling factor in two steps: 1) We converted 34 yd^3 of fly ash (calculate din Exhibit 8) to tons using the density of fly ash (2.2 tons/yd^3), which yields 74.8 tons of fly ash. 2) Next, we divided 174.8 tons of fly ash into 18 million tons fly ash (the RCC goal for 2011) which yields a factor of approximately 240,642.

In order to assess whether EPA's 2011 goal of using 18 million tons of fly ash in concrete is feasible, we calculate the volume of concrete necessary to "absorb" 18 million tons of fly ash and compare this figure to the actual volume of concrete produced annually. If the quantity of concrete necessary to absorb 18 millions tons of fly ash is less than the annual quantity of concrete produced, EPA's goal is feasible. Assuming an average mix design for fly ash of 22.5 percent in *cement* or 3.4 percent of the *concrete* mix, the use of 18 million tons of fly ash would require 523 million tons of concrete (18 million divided by 3.4 percent). We convert this tonnage estimate to cubic yards based on the density of concrete (2.03 tons/yd^3), which yields approximately 260 million cubic yards of concrete. Comparing this figure to the estimated annual production of concrete - or 400 million cubic yards, provided by Dave Goss of the American Coal Ash Association, indicates that EPA's goal is reasonable.

b. In addition to reporting energy impacts in MJ, we monetize impacts by multiplying PaLATE outputs in MJ by the average cost of electricity in 2006 ($0.0275/MJ). *Federal Register, February 27, 2006, accessed at: http://www.npga.org/14a/pages/index.cfm?pageid=914*.

c. In addition to reporting water impacts in gallons, we monetize impacts by multiplying PaLATE outputs in gallons by the average cost per gallon ($0.00234/gal). *The NUS Consulting Group, accessed at: https://www.energyvortex.com/files/NUS_quick_click.pdf.*

d. The units are presented in terms of benzene equivalents for cancer-effects and toluene equivalents for non-cancer effects on a per kilogram basis. See Hertwich et al. 2001. *Environmental Toxicology and Chemistry*. 20(4): 928-939.

e. We present Human Toxicity Potential Impacts in terms of percent change. Taking a straight difference between baseline scenario and beneficial use scenario outputs for HTP yields large numbers that may falsely suggest large, negative human health impacts when fly ash is used in concrete pavement. By presenting percent change, it is easier to see that the actual impact is in fact small.

As shown in Exhibit 9, the results of the PaLATE analysis of the initial construction of concrete pavement suggests positive environmental benefits from materials production processes. For example, cement manufacturing is an energy intensive process; to the extent virgin cement manufacturing can be reduced through beneficial use of fly ash, energy resources will be conserved. In this analysis, the use of 18 million tons of fly ash in concrete pavement results in energy savings of approximately 39 billion megajoules per year. This is equivalent to 6.4 million barrels of oil and 277 million gallons of gasoline, respectively.[51] The value of this avoided energy consumption in dollar terms is approximately $1.1 billion per year.

Reductions in CO_2 emissions are closely related to reduced energy consumption. In this analysis, partial substitution of virgin Portland cement with fly ash results in approximately 2.7 million megagrams of avoided CO_2 emissions (extrapolated). This is equivalent to removing approximately 600,000 passenger cars from the road each year.[52]

The PaLATE model also estimates 19.4 billion gallons in water savings (extrapolated), valued at approximately $45.4 million per year. Other environmental benefits presented in Exhibit 9 include reduced air emissions, such as NO_x (32.3 million kg) and SO_2 (32.8 million kg), and reductions in RCRA hazardous waste generated. We do not calculate these benefits in dollar terms as monetizing involves complex valuation procedures.

In contrast to the positive impacts of waste, emissions and energy reductions, the PaLATE model suggests that beneficial use of fly ash could potentially have negative impacts on human health risk. These impacts, however, are small. CCPs contain trace quantities of the oxidized forms of arsenic, boron, cadmium, chromium, lead, and selenium, which can have adverse effects on human health if doses occur in sufficient quantities. Relying on estimates from the Human Toxicity Potential (HTP) model, PaLATE projects that beneficial use of fly ash in concrete would cause a 1.3 percent increase in the HTP value for carcinogens and a 3.9 percent increase in non-carcinogens. More detailed assessments tend to confirm that any negative impacts to human health are likely to be small.[53]

[51] We convert the PaLATE model results for avoided energy consumption (in megajoules) to avoided oil and gasoline consumption using conversion factors provided by EPA's Waste Reduction Model (WARM). According to WARM, one barrel of oil has a heat content of 5.78 million Btu and one barrel of gasoline (42 gallons) has a heat content of 5.6 million Btu. (Note that one megajoule is equivalent to 947.82 Btu). The WARM model can be accessed at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsWasteWARMUsersGuide.html.

[52] We convert the PaLATE model results for CO_2 emissions (in megagrams) to passenger car equivalents using the web-based Greenhouse Gas Equivalencies Calculator developed by the U.S. Climate Technology Cooperative. To determine annual CO_2 emissions per passenger car, the Calculator uses the following methodology: Average vehicle miles traveled (12,000 miles) was divided by average gas mileage (23.9 miles/gallon) to determine gallons of gasoline consumed per vehicle per year. Gallons of gasoline consumed was multiplied by carbon dioxide emissions per gallon of gasoline (8.781 kg/gallon) to determine carbon dioxide emitted per vehicle per year. Dividing the resulting figure (4.4 megagrams of CO2 per vehicle per year) by the avoided CO2 emissions from the PaLATE model (2,700,000 megagrams) results in approximately 600,000 passenger vehicles per year. The Greenhouse Gas Equivalencies Calculator can be accessed at: http://www.usctcgateway.net/tool/

[53] The increase in cancer and non-cancer HTP in this analysis is attributable to a higher cancer HTP value (for water exposure) for fly ash than for Portland cement in PaLATE. For example, when fly ash replaces a portion of Portland cement in concrete, there is a decrease in cancer HTP attributable to Portland cement, but a larger increase in cancer HTP attributable to fly ash. This yields a net increase in cancer HTP. However, we suspect a possible error in the calculation of

Limitations and Assumptions

Although this analysis provides a useful example of the benefits that can be achieved through beneficial use of CCPs, it is important to recognize several limitations of the work to date:

- The PaLATE model has not undergone a formal peer-review process to ensure the accuracy and reliability of its methods and underlying assumptions.
- The PaLATE model may over or under estimate the national impacts of using recycled materials in pavement construction since site-specific environmental conditions and proximity to sources of recycled materials may affect the resulting benefits and influence the net effect of choosing recycled over virgin materials in pavement construction.
- The PaLATE environmental results are reported in physical quantities (e.g., MJ energy, gallons water, Mg CO, kg NO, g Hg, etc.), not in monetized terms.
- The analysis relies on a fixed estimate of the average transport distance between the fly ash or Portland cement supplier and the concrete manufacturing facility.

In addition to the limitations and assumptions outlined above, Exhibit 10 describes the assumptions behind the calculation of each environmental and human health impact in PaLATE.

EXHIBIT 10: SUMMARY OF PALATE MODEL ANALYSIS AND ASSUMPTIONS

	FLY ASH ANALYSIS	
IMPACTS	**LIFE CYCLE PHASE DRIVING IMPACT**	**DESCRIPTION**
ENERGY CONSUMPTION[B] (MEGAJOULES)	Materials Production	The reduction in energy consumption in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. The production of Portland cement is energy-intensive. In contrast, the assumed energy for fly ash production in PaLATE is zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production energy.
WATER CONSUMPTION[C] (GALLONS)	Materials production	The reduction in water consumption in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. Water is used in the production of Portland cement but the assumed water requirement for fly ash production in PaLATE is zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related water consumption.
CO_2 EMISSIONS (MEGAGRAMS)	Materials production	The reduction in CO_2 emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. The production of Portland cement generates high levels of CO_2 from the burning of fossil fuels (predominantly coal) during pyroprocessing and from the chemical reactions (calcination) that convert limestone into clinker. In contrast, the assumed CO_2 emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in

the HTP values for cement in PaLATE, which may overstate the magnitude of the cancer and non-cancer human health decrements calculated in this analysis.

IMPACTS	FLY ASH ANALYSIS	
	LIFE CYCLE PHASE DRIVING IMPACT	DESCRIPTION
		production-related CO_2 emissions.
NOX EMISSIONS (KILOGRAMS)	Materials production	The reduction in NOx emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. The production of Portland cement generates substantial levels of NOx as a result of the combustion of fuels at high temperatures in the cement kiln. In contrast, the assumed NOx emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related NOx emissions.
PM_{10} EMISSIONS (KILOGRAMS)	Materials production	The reduction in PM_{10} emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. PM_{10} is generated during Portland cement production from quarrying operations, the crushing and grinding of raw materials and clinker, and the kiln line. In contrast, the assumed PM_{10} emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related PM_{10} emissions.
SO_2 EMISSIONS (KILOGRAMS)	Materials production	The reduction in SO_2 emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. SO_2 is generated during Portland cement production from the combustion of sulfur-bearing compounds in coal, oil, and petroleum coke, and from the processing of pyrite and sulfur in raw materials. In contrast, the assumed SO_2 emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related SO_2 emissions.
CO EMISSIONS (KILOGRAMS)	Materials production	The reduction in CO emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. CO is generated during Portland cement production from the combustion of fossil fuels for process heat and electricity. In contrast, the assumed CO emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related CO emissions.
Hg EMISSIONS (GRAMS)	Materials production	In this analysis there is a small reduction in Hg emissions when fly ash replaces a portion of Portland cement in concrete. The production of Portland cement generates very small quantities of Hg; assumed Hg emissions for fly ash production in PaLATE are zero. Thus, the incremental reduction in Hg emissions from partial replacement of Portland cement with fly ash is in one cubic yard concrete is very small. However, when this small reduction is extrapolated, it becomes more appreciable. It should be noted, however, that as with other impacts reported by PaLATE, the magnitude of Hg emissions is not necessarily indicative of environmental or human health damages.
Pb EMISSIONS (GRAMS)	Materials production	The reduction in Pb emissions in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. Pb emissions are released during Portland cement production but the assumed Pb emissions for fly ash production in PaLATE are zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related Pb emissions.

IMPACTS	FLY ASH ANALYSIS	
	LIFE CYCLE PHASE DRIVING IMPACT	DESCRIPTION
RCRA HAZARDOUS WASTE GENERATED (KILOGRAMS)	Materials production	The reduction in RCRA Hazardous Waste in this analysis results from avoided Portland cement production when fly ash replaces a portion of Portland cement in concrete. RCRA hazardous waste is generated in Portland cement production, primarily from managing hazardous waste that is burned as a fuel source. aLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). In contrast, the assumed hazardous waste generation from fly ash production in PaLATE is zero. PaLATE assumes zero environmental impact for fly ash production because fly ash is a byproduct of another production process (electricity production). Thus, partial replacement of Portland cement with fly ash results in a net decrease in production-related RCRA hazardous waste.
HUMAN TOXICITY POTENTIAL (CANCER)	Materials production	The increase in cancer human toxicity potential (HTP) in this analysis is attributable to a higher cancer HTP value (for water exposure) for fly ash than for Portland cement in PaLATE. Thus, when fly ash replaces a portion of Portland cement in concrete, there is a decrease in cancer HTP attributable to Portland cement, but a larger increase in cancer HTP attributable to fly ash. This yields a net increase in cancer HTP. However, we suspect a possible error in the calculation of the HTP value for cement in PaLATE, which may overstate the magnitude of the cancer human health decrement calculated in this analysis.
HUMAN TOXICITY POTENTIAL (NON- CANCER)	Materials production	The increase in non- cancer human toxicity potential (HTP) in this analysis is attributable to a higher cancer HTP value (for water exposure) for fly ash than for Portland cement in PaLATE. Thus, when fly ash replaces a portion of Portland cement in concrete, there is a decrease in non- cancer HTP attributable to Portland cement, but a larger increase in non-cancer HTP attributable to fly ash. This yields a net increase in non-cancer HTP. However, we suspect a possible error in the calculation of the non-cancer HTP value for cement in PaLATE, which may overstate the magnitude of the non-cancer human health decrement calculated in this analysis.

WARM MODEL ANALYSIS

The Waste Reduction Model (WARM) was created by the EPA to help solid waste planners and organizations estimate greenhouse gas (GHG) emission reductions from several different waste management practices.[54] WARM calculates GHG emissions for baseline and alternative waste management practices, including source reduction, recycling, combustion, composting, and landfilling. The user can construct various scenarios by entering data on the amount of waste handled by material type and by management practice. WARM then automatically applies material-specific emission factors for each management practice to calculate the GHG emissions and energy savings of each scenario. The model evaluates energy use and GHG emissions in three stages of the life cycle: (1) raw material acquisition, (2) manufacturing (fossil fuel energy emissions), and (3) waste management (carbon dioxide emission associated with compost, non-biogenic carbon dioxide and nitrous oxide emissions from combustion and methane emissions from landfills). At each of these points, the study also considers transportation-related energy use and GHG emissions.

---

[54] WARM can be accessed at http://yosemite.epa.gov/oar/globalwarming.nsf/WARM?openform. Version 7 of the model, which was used for this analysis, was last updated in August 2005.

The WARM model reports avoided lifecycle GHG emissions in either metric tons CO_2 equivalent ($MTCO_2E$) or metric tons CO equivalent (MTCOE), as well as energy use in BTUs. In addition, the model converts these outputs to equivalent metrics including the equivalent number of cars removed from the road in one year, the equivalent number of avoided barrels of oil burned, and the equivalent number of avoided gallons of gasoline. Currently, the only CCP available for analysis using WARM is fly ash. WARM calculates GHG emissions and energy use associated with use of fly ash in concrete as an alternative to landfill disposal. We first estimate the incremental benefits of beneficially using one ton of fly ash in concrete using the WARM model in comparison to disposing of that ton of fly ash in a landfill. Then, we extrapolate the results to estimate benefits associated with attainment of the 2011 RCC goal of beneficially using 18.6 million tons of fly ash in concrete.[55]

Results

Exhibit B-1 presents the results of the WARM model analysis for the beneficial use of fly ash.[56] The WARM model estimates that a ton of fly ash beneficially used in concrete results in avoidance of approximately 0.91 $MTCO_2E$ of GHG emissions and 5.29 millions BTUs of energy use. Extrapolating these outcomes to the 2011 RCC goal of beneficially using 18.6 million tons of fly ash in concrete, results in avoidance of nearly 17 million $MTCO_2E$ of GHG emissions. According the WARM model, this is equivalent of removing approximately 3.7 million cars from the road. In addition, attaining the 2011 goal results in the avoidance of 98.5 million million BTUs of energy use or 104,000 terajoules. This is equivalent of energy consumption of nearly 520,000 households or approximately 787 million gallons of gasoline.

[55] WARM allows the user to define key modeling assumptions, such as landfill gas recovery practices and transport distance to MSW facilities. For landfill gas (LFG) control, we select the "National Average" setting, which calculates emissions based on the anticipated proportion of landfills with LFG control in 2000. For transport distances, we use the default setting (20 miles).

[56] It is important to note that the results reported by WARM for avoided greenhouse gas emissions and avoided energy use may not be directly comparable to those reported by the BEES model or PALATE model due to differences in the methodologies (including life cycle system boundaries) employed by each model.

EXHIBIT B-1 WARM RESULTS: IMPACTS OF BENEFICIAL USE OF FLY ASH IN CONCRETE

IMPACT	INCREMENTAL IMPACT OF REUSING 1 TON OF FLY ASH	TOTAL IMPACTS OF MEETING RCC GOAL[a]
GHG EMISSIONS AVOIDED	0.91 $MTCO_2E$	16,918,893 $MTCO_2E$
EQUIVALENT NUMBER OF PASSENGER CARS REMOVED FROM ROADWAYS		3,661,098 cars
ADDITIONAL ENERGY USE[b]	5.29 million BTUs	98,469,819 million BTUs $2.52 billion
EQUIVALENT NUMBER OF HOUSEHOLDS ANNUAL ENERGY CONSUMPTION		519,904 households
EQUIVALENT NUMBER OF GALLONS OF GASOLINE		787,308,665 gallons of gasoline

Sources:

1. US EPA, *Solid Waste Management and Greenhouse Gases, A Life cycle Assessment of Emissions and Sinks*, 2nd Edition, May 2002. (EPA530-R-02-006) (WARM Model)
2. US EPA, *Background Document for Life cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete,* November 2003. (EPA530-R-03-016)

Notes:

a. The total impacts of meeting RCC goal represent the difference between beneficially using 18.6 million tons of fly ash in concrete in comparison to disposal in a landfill.

b. In addition to reporting energy impacts in BTU, we monetize impacts by multiplying 98,469,819 million BTU by the average retail price of electricity for all sectors in 2006 ($0.0874/KWh or $0.0256/1,000 Btu). (Source: Energy Information Administration, "Electric Power Monthly – Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector," accessed on October 10, 2006 at: <http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html>.)

Limitations and Assumptions

Although the WARM analysis provides a useful example of the energy use and GHG emissions benefits that can be achieved through the beneficial reuse of fly ash in concrete, it is important to recognize some of the key limitations of the work to date:

- Our analysis assumes a 20-mile transport distance from the point of collection to the landfill or concrete facility. In reality, transport distances may be greater or less than 20 miles. Adjusting transport distance would effect both GHG emissions and energy use.
- Emissions factors used in WARM reflect national averages. Our analysis may therefore over or under estimate impacts for a specific region or location. In addition, we use a national average for landfill gas recovery that may also over or understate emissions for a specific landfill.
- WARM does not specifically calculate impacts on purchased energy. Purchased energy impacts may be incorporated into the avoided energy use metric, but this is not clear.
- WARM reports some environmental impacts in physical quantities (e.g., BTUs energy, lbs NOx, etc.), not in monetized dollar effects.